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ECONOMIC FOUNDATION OF NATURAL RESOURCES

III

Ground-Water Regions of the United States— Their Storage Facilities

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Foreword

WHILE THE PATTERN of surface-stream flow is generally known and the potentials of surface reservoirs on the principal rivers have been extensively appraised there has been only limited study of the Nation's subsurface facilities for the management of water and appraisal of their potentials is still but a fragment of what is needed.

Ground-water studies to date have been predominantly in problem areas—areas concerned with falling water tables, failure of wells, impairment of water quality or other troubles—often the result of utilizing a complex resource without a clear perspective of its physical and economic features for guidance in development.

The physical features of subsurface water control facilities are generally complex as also are the forces governing recharge, transmissibility, and the rate and costs of water withdrawal. The presence or absence of a facility that may be suitable for water management can usually be inferred if there is sufficient understanding of the basic geology of the area, but it is only by careful mapping and exploration of all the vital factors involved that the extent of its possible use can be judged and the essential features of a program for its development formulated.

Recent reconnaissance type studies have added to the knowledge of the geographical distribution of the Nation's ground-water resources and provided the base for enlarged estimates of the magnitude of the unutilized potentials. More detailed studies in limited areas have clarified a few of the complex features of effective management technique.

This number III in the series on The Physical and Economic Foundation of Natural Resources provides a general description of the principal types of ground-water reservoirs in various parts of the country. A second manuscript (in preparation) will supply more detailed portrayals of the facilities in several areas selected to illustrate different types of natural mechanisms of water control.

Introduction

WATER-RESOURCE PROBLEMS are involved in more ways in the field of functioning of the Interior and Insular Affairs Committee than any other resource. It is a basic resource on which the Federal Government is not only spending more money than any other, but probably more than all others combined. Yet there is much we need to learn about its basic features.

Some of the neglected features of the scientific foundation in natural resources have been set forth in the first two documents in this series: I Photosynthesis—Basic Features of the Process and II The Physical Basis of Water Supply and Its Principal Uses. In this volume we come up with a third: III—The Ground-Water Regions of the United States, Their Storage Capacities.

On the basis of preliminary reports it became evident that the field of greatest neglect in our present program of scientific research as it relates to water resources is in underground water studies. From a survey made at my request Dr. J. R. Mahoney, senior specialist in natural resources of the Legislative Reference Service of the Library of Congress thus described this deficiency.

1. The physical features of the subsurface geological formations that can be used for the management of water resources are varied and complex, differing markedly from place to place and requiring careful studies to reveal their physical features sufficiently to permit determination of their potentials in water-conservation programs.

2. The research program in underground water resources has been so limited that not more than 10 percent of the ground-water reservoirs of the United States have had sufficient study to determine their potentials in more than a preliminary way.

3. These limited studies are not well distributed over the country but rather are highly concentrated in areas where difficulties have already developed. Many of these studies have been devoted to determining how difficulties, often created by unwise development of the resource, can be corrected. Had these studies been completed in time to serve as a guide prior to use the resource could, in many cases, have been developed without trouble and with far greater effectiveness.

4. The location and nature of these investigations are determined predominantly by State and municipal cooperators with the Federal program. The regular annual appropriations to the Geological Survey contains the language:

> *Provided*, That no part of this appropriation shall be expended in cooperation with States or municipalities except upon the basis of the State or municipality bearing all of the expense incident thereto, in excess of such an amount as is necessary for the Geological Survey to perform its share of general water resources investigations, such share of the Geological Survey in no case exceeding 50 per centum of the cost of the investigation. * * *

This has the effect of restricting the program to the areas and problems designated by the cooperating agency, since the amounts of money available for matching are usually almost equal to the total Federal appropriations for ground-water studies, leaving only a limited amount free for general studies and for areas that have not been designated by the cooperators.

5. These features of the ground-water program would be far less serious if there were adequate personnel in universities and the State agencies devoting time to study of this vital resource. But this is not the case. To an unusual degree the professional ground-water scientists and engineers are concentrated in the United States Geological Survey. The typical arrangement in the cooperative studies is for the Survey to furnish the trained personnel and for the travel, office, and other expenses to be defrayed by the State or local agency.

These factors have been of sufficient influence to severely limit studies so that most of the ground-water resources of the country are unknown or only partly explored. It seems evident, however, that the careful study of these resources is a prerequisite to the sound planning of water projects in all areas where useful subsurface facilities exist for the channeling and storage of water.

We are, however, faced with a serious dilemma since suitable studies are complex and will require time and there is only limited professional help available. It was this difficult situation that caused me as chairman of the committee to support the program that Dr. Mahoney already had under way and to request that he continue to seek the cooperation of the Geological Survey and available personnel from the universities to make a series of reconnaissance surveys and provide reports that would furnish preliminary appraisal of the areas of potential ground-water resources of the country and to clarify the general principles of how these resources can be most effectively used.

The first manuscript is now available and is being printed for the use of the committee and others who may be concerned or interested. A second document is in course of preparation and will soon be available. These two publications will add significantly to the available literature in the field.

The great mass of our regulatory legislation pertaining to fresh water and its uses takes into consideration for the most part only surface water flowing in streams or impounded in reservoirs, and yet at many places surface flow and surface storage together probably constitute only a small part of the existing supply of fresh water available to man. That other

part, which I have assumed to be the major portion, is underground waters, the exact measurement of which we have not yet been able to compute adequately. It has long been my belief and hope that we should attempt more adequately to measure our underground water supply. This is apparently the one part of the hydrologic cycle which seems least known to science.

We have long recognized how important stream flow is and how much more important surface storage later becomes to reclamation, but it is only in recent times that the presence of underground storage has become very significant to irrigation agriculture. In the early days of farming in the semiarid West the pioneers threw brush diversion dams into the western streams and diverted the all too meager stream flow onto their cultivated lands. Western streams being erratic, the farmers found that sometimes flash floods washed out their brush dams and at other times the streams went dry in the midst of summer and the growing season. Thus the farmers saw the need of building great permanent storage dams to catch and store the floodwaters and hold them until they were most needed in the dry season. In this way irrigation agriculture grew in importance and productiveness.

Recently it has become evident that there is often under the dryest desert land a quantity of water which may be within feasible pump lift of the fertile land above and man has begun to utilize this underground supply. In view of the fact that there is no evaporation from the underground reservoirs while there is heavy loss by evaporation from the surface reservoirs, it is also evident that underground storage for that reason is better than surface storage, if man can measure and control it. In certain areas recently more water has been pumped from underground storage for irrigation than has been diverted from surface storage. One draw-back is our lack of knowledge of the water storage underground and especially of the conditions of that storage and the behavior of that water, as well as the quantity of it.

Some areas in the United States have been the subject of very careful study, as for instance the South Coastal Basin of California. Accordingly, for that particular area it is possible to obtain more adequate answers to my four questions enumerated in an earlier publication than would be true of some other areas, but it is safe to say that no area in the semiarid section has been adequately studied from the standpoint of natural discharge and recharge of water enough to make the inhabitants of that area feel safe in relying on the use of pumped water.

This lack of knowledge and security applies, of course, to domestic use, to municipal use, to reclamation use, and perhaps more than all others to industrial use. Industrial uses make a heavier drain upon the given water supply and they also usually call for long-time permanent investments which may not be safely hazarded because of lack of information. The cost of putting down big wells and deep wells is a gamble almost like drilling for oil.

Even in irrigation farming a man might be willing to venture to pump water without knowing the quantity available to grow annual crops where he could not safely venture to put out a citrus grove or other plants requiring years of development before coming into production. The latter would be a more expensive capital investment, which might be a failure because of lack of water. This is even more to the point where great capital investments are made in industrial facilities requiring unusual quantities of water from wells that might go dry. Hence, the great desirability of knowing the water immediately under our feet.

JOHN R. MURDOCK, *Chairman,*
Committee on Interior and Insular Affairs,
House of Representatives.

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Status of Ground-Water Studies

ALBERT NELSON SAYRE, Chief, *Ground-water Branch, United States Geological Survey*

THE GROWING PROBLEMS of water supply that have plagued various sections of our country during the past few years have focused increasing attention on the need for careful consideration of the best methods for assuring the best use of the water resources available to us. The seriousness with which the public and the Government have viewed the situation is shown by the number of commissions and survey groups that have been appointed by scientific and professional societies, by State governors, and by the President of the United States to study the Nation's water problems and to recommend measures for their solution. The readiness with which men of high professional, educational, or political standing have accepted the responsibility and have given unstintingly of their time and talent in order that the best solutions might be reached merits the highest praise.

These groups have produced a number of excellent, carefully considered reports which have included specific recommendations for the conservation and proper development of our water resources. They have called attention repeatedly to the need for more adequate basic data and for greatly increased attention to the analysis and interpretation of these data. However, the main consideration generally has been given to the control or conservation and utilization of water at or near the surface, or to the engineering or political organizational pattern that has been considered to be best adapted for planning, designing, and constructing the facilities needed for such control.

This attention to the surficial part of the hydrologic cycle is not surprising. This part is the most readily visible and, at least so far as the layman is concerned, the most readily understandable phase of the cycle. Moreover, the prospect of bringing the raging torrents of destructive floodwaters under control by levees, dams, or "upstream engineering" has a compelling and dramatic appeal. However, to control the surface water, although highly essential for the prevention of floods, is only a partial answer to the problem of optimum use of our water resources. It fails to take into account the enormous reservoirs of ground water that lie hidden beneath the surface. These reservoirs receive recharge from precipitation and from river channels and surface reservoirs, store it, and eventually discharge it as springs or seeps into surface streams, and thus maintain the flow of streams during dry weather. Therefore, any serious attempt to conserve water resources and to utilize them to the best advantage must take into consideration not only surface water, but also the entire hydrologic cycle, including precipitation, soil moisture, and ground water.

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The concept of the hydrologic cycle is quite simple. The precipitation, which is the source of essentially all our water supply, falls upon the ground and is either evaporated or is absorbed by the soil, except when the precipitation rate exceeds the capacity of the soil to absorb it. In this case the excess water runs off over the land surface and enters streams or lakes, to return eventually to the sea. Of the water that enters the soil, the greater part is held in the soil and eventually is drawn back to the surface by plants or by capillarity. A part of it may pass downward and enter the ground-water reservoir, whence it moves laterally toward a lower elevation and eventually returns to the surface as springs or seeps.

In reality, the hydrologic cycle is extremely complex. Especially that part of it that occurs beneath the land surface, and therefore is invisible, is surrounded with misunderstanding and misconceptions. Among these is the common but erroneous belief that all water that is absorbed by the soil becomes ground water; that there is a continuous water table beneath the land surface; that this water table is declining throughout the United States and so on.

It seems strange that in an age when even the children are accustomed to speaking glibly and understandingly of electronic devices, jet propulsion, and nuclear energy, ground water is regarded by a great many people as being no less mysterious than it appeared to our forebears of the Middle Ages, who often explained it by means of supernatural phenomena. Indeed, many persons who are well acquainted with such involved equipment as Geiger counters or oscilloscopes, or with the works of the great philosophers or political scientists, or with the military campaigns of Alexander, Napoleon, and Caesar, or with the most intricate details of vast construction projects as Bonneville Dam on the Columbia or Aswan Dam on the Nile, still feel that the occurrence of ground water, its replenishment, movement, and discharge, are so mysterious as to defy scientific explanation; that it can be understood and "located" only by persons ("water dowsers" or "witches") who are supposedly possessed of occult powers or by the use of instruments whose operations are as mysterious as their operators.

As a matter of fact, the bizarre and supernatural theories of the Middle Ages—in ground water as in most other matters—have been superseded by understanding based on the slow but certain advance of scientific knowledge. The puzzling and apparently mysterious complexity of the occurrence of ground water results to a very large extent from the complex geologic history of our earth. It results

from the fact that our continent, which now appears so stable and permanent, has been subjected during eons past to uplift and erosion, sedimentation and folding and faulting, deep-seated intrusions of molten rocks and surficial outpourings of lava, invasions of the land areas by the sea, and burial under huge masses of glacial ice advancing from the mountains or the frigid north.

The geologic history through which any particular area has passed very largely influences the hydrologic cycle in that area. If the history has been such as to form layers of sand, the soil probably will be sandy and will readily absorb rainfall. Thus, there will be a minimum of runoff over the land surface and of soil erosion. The streams will reach flood stages only during very heavy storms and they will tend to have a uniform, steady flow even during dry weather. Drilled or dug wells probably will produce large amounts of water. On the other hand, if the history has been such that the underlying beds are dominantly clay or silt, the soil will be clayey or silty and will absorb water with difficulty. Storms of relatively small magnitude will cause substantial overland runoff and a maximum of soil erosion and production of silt for the streams to carry. The streams will flood frequently and will tend to dry up during even moderate droughts. Wells will produce relatively little water, and in some places none at all. Inasmuch as the geologic history is infinitely varied in different parts of the country, the number of variations to the simple examples cited is likewise infinite. Thus the geologic and ground-water conditions of a stream basin have an effect on the stream regimen that varies from place to place. It is necessary, therefore, to understand the ground-water conditions and their relation to stream discharge and to take these into consideration in designing water-use facilities, if the water resources are to be used to the best advantage.

The determination and appraisal of the ground-water resources is slow and time-consuming work. Although the general geologic and ground-water conditions throughout the country are known, the detailed information necessary for practical solution of the over-all water-resources problem is known only for a small percentage of the Nation.

Consequently, it is desirable to call the attention of the public, and particularly of those segments of the public that are influential in directing the course of development of our natural resources, to the character and occurrence of ground water and to its relation to precipitation, to land-management practices, to stream flow, and to water-resources development. In order to promote this understanding, the Geological Survey was pleased to have the opportunity to release a ground-water geologist of long and varied experience, Dr. Harold E. Thomas, to the Conservation Foundation in 1949 for the purpose of carrying out a survey of the ground-water situation in the United States. Dr. Thomas has carried out a general review of ground-water conditions throughout the Nation, which would have been a proper activity of the Federal Government if the necessary funds had been available. It has been published in an excellent and instructive book entitled "The Conservation of Ground Water."

Somewhat earlier, Dr. J. R. Mahoney, senior specialist in natural resources of the Legislative Reference Service of the Library of Congress, was assigned the task of reexamining the Federal activities in the field of natural resources. This project was sponsored by the Committees on Interior and Insular Affairs and resulted in the publication in 1950 of House Document 706, A Program to Strengthen the Scientific Foundation in Natural Resources, in which the Geological Survey was privileged to present, by the request of the committee, a chapter entitled "An Accelerated Program for Obtaining Basic Data and Promoting Research on the Nation's Water Resources."

The present paper by Dr. Thomas provides a description and discussion of ground-water occurrence and resources in the 10 major ground-water regions of the United States. In this paper we are particularly interested in discussing the facilities which Nature has provided, through the geologic framework, for the storage of water in ground-water reservoirs.

Still another paper is in preparation which, it is hoped, will further clarify the concepts of ground water. Both papers have been prepared at the request of Dr. Mahoney for the Committee on Interior and Insular Affairs. The second paper will present in moderate detail hydrologic descriptions of certain selected areas in the United States together with suggestions for the conservation of water through measures of water management that appear to be applicable to the geologic and hydrologic situation in each of the areas.

Ground-Water Regions of the United States—Their Storage Facilities

HAROLD E. THOMAS, *United States Geological Survey*

Introduction

THE IMPORTANCE OF SUBTERRANEAN WATER

THE SCIENCE of hydrology would be relatively simple if water were unable to penetrate below the earth's surface. All operations of the hydrologic cycle could then be determined by measurements of precipitation, runoff, and evaporation. It is fortunate that this is not the case, for the water that *does* penetrate below the land surface sustains all plant life upon the land. Thus the earth (using the term to include all types of rock, gravel, sand, clay, and soils and their included vegetative matter) provides storage space for water that is withdrawn by plant life as required, as long as it is available. In many places, underground storage facilities can be adapted similarly to meet the water requirements of man.

Our knowledge of subterranean water is by no means proportionate to its importance in our civilization. This lack of knowledge results largely from the fact that the paths of movement of underground water cannot be watched, as those of surface water can be. Nature provides observation posts only at points where water enters the ground, where it leaves the ground, and at very few places in caverns along the route. By well construction, mining, tunneling, and other excavations, man has added hundreds of thousands of other places where he can collect data concerning water beneath the land surface. Although these potential observation points are numerous, they represent in the aggregate a negligible proportion of the total volume of rock materials through which water may move, and in large areas our concepts of the occurrence of subterranean water are based on inferences. Nevertheless, the collected data form the basis for a good working knowledge of the physical principles governing the movements of subterranean water.

Another factor in the incompleteness of our knowledge is that a great variety of basic data must be collected and analyzed in order to understand the underground phases of the hydrologic cycle in any specific area. When water enters the ground, it moves into a porous medium. Its movements are then controlled not alone by its own physical properties, but also by the properties of the rock material. The quantity that is in storage and the rate of its movement can be determined, but the operations are more difficult than are the equivalent determinations for surface water, because they require data concerning the rock material as well as the water.

SOIL MOISTURE VERSUS GROUND WATER

The water beneath the land surface is not all ground water. A man with his feet on the ground might assume that by picking up a handful of moist earth he obtains some ground water, or that in pouring a bucketful of water upon absorbent land he increases the ground-water resources by that amount. These assumptions would be incorrect. *Ground water*, by definition, is only that part of the subterranean water that occurs where all pores in the containing rock materials are saturated. The *zone of saturation* may extend up to the land surface in some places, notably in seep areas and in some stream channels, lakes, and marshes. At all other places there is, above the ground-water zone, a *zone of aeration* that may range in thickness from a few inches to hundreds of feet.

Some water is in the zone of aeration at all times, held there by molecular attraction. In particular, soils may hold significant volumes of water against the downward pull of gravity. Commonly each foot of soil holds 0.4 to 1 inch of water so tightly that it cannot be removed by plants or gravity; the soil may also retain 2 or 3 inches of *capillary* water against the force of gravity, but not against the pull of plants (Croft and Hoover, 1951). It is this capillary water that most plants use in growth, and soil moisture is therefore of the highest importance to agriculture. Although the supply is depleted as plant roots extract the water, it may be replenished by infiltration of water from rain and snow or of water applied for irrigation. Wells cannot extract any of the water suspended in the soil zone: they must be drilled through the zone of aeration and obtain their supplies from ground water.

Most ground water, like soil moisture, is derived ultimately from precipitation. There are other sources of ground water: water rising from the earth's interior to the surface for the first time, as in some volcanic areas; water that was trapped in some rocks at the time of their deposition; water contained in certain minerals and released when those minerals decompose. But these sources yield a negligible proportion of the total ground-water supplies, and commonly the water is too mineralized for most uses. Thus essentially all usable ground water was once rain or snow melt which infiltrated into the soil or other earth material at some point, percolated to the zone of saturation, and then may have moved underground for some distance before reaching its present position. Over most of the Nation the surficial materials are soils,

which in some places support forests or grasses or other native vegetation, in others they support cultivated crops. In relatively small areas bare rocks, boulders, or gravel constitute the surficial materials. The principles governing the storage and movement of water in these surficial materials, as well as in the underlying earth materials, are discussed in the next chapter.

Rules of Conduct For a Particle of Water

The American Water Works Association, in order to emphasize the importance of water to the customers of its members, has created a personality known as "Willing Water." He is introduced into this discussion in the hope that he may be able to state his case without too much scientific lore. It is understood that his ancestors have long been a part of one of our typical oceans, so that there is no reason to suppose that Willing Water has any foreknowledge of the environment in which he is to be dropped.

Gravity is a dominant force throughout Willing Water's career on or in earth. Whether he is Nature's child or is sired by the rainmaker's chemicals, he is brought down from the atmosphere by that force. Upon landing he will continue downward as long as there is an opening through which he can move. If surface slopes or inclined shafts are more accessible than vertical openings, he is not at all averse to them.

It is not necessary that water affected by gravity move continuously downward, as can be demonstrated in any town where water is distributed from an elevated tank. The water will flow through horizontal mains and even upward into a bathtub above the ground. But to reach that bathtub it must be pushed by other water that is descending because of gravity. Similarly Willing Water under certain natural conditions and in certain places underground moves horizontally, and even upward.

Willing Water generally can run down a steep slope faster than a gentle one. Underground also, the gradient is an important consideration, but there his rate of progress depends to a great extent upon the obstacles in his path. Practically all underground movement is an obstacle course through rock materials and therefore the rate inevitably is slower than stream flow down a comparable slope. Even so, the openings in some materials are sufficiently large and interconnected to give him the equivalent of a four-lane highway, whereas others provide descents more narrow and tortuous than a mountain trail.

Willing Water can disperse into a film thin enough that he can resist the force of gravity. Let Willing Water wash your hands and you cannot shake him off entirely. The smaller the rock particle, the greater is the proportionate surface area for him to cling to in any unit volume. This is the reason for the importance of molecular attraction in fine-textured rock materials. Where these fine materials lie immediately above the zone of saturation, Willing Water may be able to rise as much as several feet by capillary action against the force of gravity.

Like a small boy with candy, Willing Water has a facility for absorbing some of the mineral matter with which he comes in contact. All minerals are soluble to some extent, and some (like rock salt, gypsum, and limestone) are far more soluble than the average. Willing Water naturally gains most of his dissolved mineral constituents while he is serving as subterranean water, where he is continuously in contact with rock materials. The opportunities for him to pick up mineral matter in rivers and lakes, however, are increasing with the population and industrialization of the Nation.

Also like a small boy, there may come a time for upchucking, and leaving behind some of these mineral constituents. These deposits, whether at spring orifices, in soils, or somewhere in the earth's interior, may result from changes in temperature or pressure, or from chemical reactions with other dissolved matter. If Willing Water goes to Heaven, he must leave his mineral constituents behind: in the soil, in alkali flats, in lakes and ponds, or wherever he takes off.

Solar energy is also important in Willing Water's career, for it is an uplifting force that will get him back to Heaven if it can. At the earth's surface he is subject to evaporation, and even below the ground he may be evaporated from the soil, or he may be pulled up by plant roots and then returned to the atmosphere. As ground water beyond the reach of plant roots, he is safe from evapotranspiration (or was until man came along with his deep-well pumps). So long as he avoids the pull of solar energy, Willing Water continues to be dominated by the force of gravity, and he may eventually reach the ocean. There, as full of salts as his ancestors, he becomes useful chiefly for navigation and recreation, until solar energy catches him up again.

Thus Willing Water is faithful to three disciplines: gravity, solar energy, and molecular attraction. His activities are based on well-established natural laws, and rather commonly he seems intent upon following the path of least resistance. However, charting his course through the hydrologic cycle is anything but simple, as mankind has learned by experience. He may not enter a well that was constructed for him, and he may refuse to stay in a reservoir that was intended to hold him. He may fall on permeable soil with such a splash that he "puddles" the soil and thus destroys his opportunity for infiltration. On the other hand, he may force himself through rocks which at first glance would appear to be impermeable enough to be shunned by him.

These vagaries make the science of hydrology, and particularly ground-water hydrology, complicated and fascinating. In large part the complications are caused by the earth materials through which water may pass, or refuse to pass. Each year there is some progress in our efforts toward a better understanding of water in relation to these materials, although the goal of adequate understanding of all sections of the country is still far in the future. The following chapter is a brief, semitechnical summary of the present status of our information concerning these relations.

The Porous Medium

ALL SUBTERRANEAN water occurs in open spaces within the rock materials of the earth's crust. There are many kinds of rocks, and in the number, size, and shape of their open spaces they differ greatly. Such loose materials as sand, gravel, and rock fragments have pore spaces that are easily seen, whereas the spaces between particles of clay and other fine-textured materials may be exceedingly minute. Some rocks have pores so numerous that the rock is hardly more than a froth of solid material. Of the so-called solid rocks, some contain pores that are microscopic, others have caverns large enough to admit a railroad train or a convention; still others are exceedingly dense and compact, but even these are commonly fractured or jointed enough to form some openings that can admit water. All openings underground may be regarded as pores, for even the largest of caverns is no more than a pore in comparison to the size of the earth. The ability of rock material to hold and yield water is determined largely by the characteristics of those pores.

The term *porous* is applied to various substances that contain openings or pores but that may differ rather widely in other properties. For instance, a sponge can absorb a large quantity of water and retain it until it is squeezed out; on the other hand, porous clothing permits a circulation of air that prevents accumulation of moisture. Similarly, porosity of rock materials may or may not be indicative of the water that can be obtained from them.

Porosity and Permeability

Porosity, the property of containing pores, is commonly expressed as a percentage—the percentage of the total volume that is *not* occupied by solid material. For example, a 1-foot cubic box containing eight 6-inch cannonballs is 52.4 percent cannonball and therefore has 47.6 percent porosity. In the more compact cannonball arrangements at Gettysburg, a cubic foot may contain as little as 26 percent of pore space. The same box could be filled by spheres of any other size, ping-pong balls, or radish seeds, or microscopic particles, and the porosity would vary within these same limits, depending upon the arrangement of the spheres. The porosity may be the same whether the spheres are large or small, provided all particles are uniform in size. However, in a mixture of cannonballs, ping-pong balls, and radish seeds the pore space would be far less than in a volume containing spheres of only one size, for the smaller spheres would occupy some of the pores between the larger spheres. Pore space varies also with the shapes of the particles, whether balls, slivers, angular fragments, or other shapes.

Similarly in nature, porosity of loose rock materials varies with the arrangement, shape, and degree of assortment of the particles. The size of grain is not a determining factor, because if other conditions are the same, a material will have the same porosity whether it consists of large or small grains. Clay, consisting entirely of minute particles, may have a porosity as great as coarse gravel, although of course the pores are not so easily seen. In some consolidated rocks the original porosity has been reduced by compaction, or by deposition of cement in the pore spaces. In others it has been increased by development of fractures, or by dissolving of some of the rock material.

Rocks of low porosity necessarily are limited in their capacity to absorb, hold, or yield water. Such rocks may occur close to the earth's surface, although the porosity is likely to decrease with increasing depth.

In rocks such as quartzite and granite most of the water is in fractures within a few hundred feet of the surface, and comparatively little water is to be found at greater depths.

The least porous rocks are probably those that are buried so deeply that the weight upon them is sufficient to close all pores—a depth that is obviously greater for strong rocks than for weak rocks. The depth at which pressures are great enough to force closure of pores in *all* rocks—that is, the depth to the *zone of rock flowage*—is greater than the 4 miles that has been penetrated in the deepest oil-test wells, and is believed to be 10 miles or more. The top of the zone of rock flowage is the theoretical lower limit to which ground water will penetrate. Evidence from deep wells indicates that in most places water becomes very scarce far above that theoretical depth. A few wells have obtained water from rocks at depths of more than 2 miles, but most deep wells have found little water below a depth of half a mile.

Rock materials of high porosity may be capable of yielding copious quantities of water, but this is not necessarily true. One saturated rock may yield most of the water contained in its pores to wells or springs; another, although having equal porosity but smaller pores, may retain practically all its water and yield negligible quantities to wells. Here, where the porosity is identical, the difference is in the proportion of the contained water that is held by molecular attraction, and the proportion that can be moved by gravity or hydrostatic pressure. The rock that permits water to move through it by gravity is far more *permeable* than the one that holds water by molecular attraction. *Molecular attraction* becomes more and more significant with decreasing size of pore, because of the increased surface area of solid material to which water can adhere.

In a cubic foot of well-sorted gravel whose particles are a

quarter of an inch in diameter, the combined surface area of the grains is about 200 square feet, or about the floor space of an average living room. In a well-sorted clay with rounded grains 0.001 millimeter in diameter, the porosity may be equal to that of the gravel; but the surface area of the grains in a cubic foot is about 1,000,000 square feet, which is 17 times the area required for a football field including its end zones.

The earth contains some pores so minute that water is held in them by molecular forces far more powerful than gravity. This is commonly true of loose materials that contain a sizable proportion of clay-sized particles. Because of these molecular forces, soils are capable of retaining considerable quantities of water within their pores. Because of these forces also, saturated clays may yield only negligible quantities of water to wells; in laboratories, that water can be dislodged only by forces several times as great, and even several thousand times as great, as gravity.

The water retained in pores by molecular attraction is of major economic importance, provided it is close enough to the surface that plant roots can reach it. Small pores give soils their water-holding capacity, and provide the water that is used by crops throughout the intervals between rainstorms. Clean gravels, having only large pores, readily absorb water from precipitation but are too permeable to hold it near the surface; they are therefore likely to support very little vegetation.

Below the depths that can be reached by plant roots, the water dominated by molecular forces cannot be of major economic importance, because it is not yielded readily to wells or springs where mankind can put it to use. However, the force of gravity continues to operate even upon waters in those minute pores, so that small quantities of water may be yielded to wells in time. Thus there is slow drainage of water into many wells dug into clay, or other fine-textured materials, sufficient to meet the needs of limited domestic and stock use. In some areas of heavy pumping the slow drainage from saturated clays has been accompanied by compaction, and has caused subsidence of the land surface.

The rate of movement of water beneath the surface is dependent to an important degree upon the permeability of the rock material, which is its capacity for transmitting water under pressure. In permeable materials, gravity is the force that moves water downward from the land surface to the zone where all pores are saturated, thence laterally toward lower elevations, and ultimately to places where the water is discharged at the land surface by springs or seeps, or by evaporation or transpiration.

The rocks of low porosity are generally impermeable because of the dearth of avenues for movement. Rocks with isolated pores are similarly impermeable. As shown above, rocks of high porosity may also be impermeable if their pores are so small that the water is held in them by molecular forces.

In the development of ground water by means of wells, a hole is drilled into the zone of saturation. Water that drains from the saturated rock materials into the well is called *gravity ground water*. As that water is pumped out, the reduced hydrostatic pressure at the well causes movement of other water toward the well. The rate at which water moves toward the well, and therefore the rate at which water can be withdrawn from the well, depends in large part upon the permeability of the materials from which the water is drawn.

The Aquifer or Ground-Water Reservoir

The science of geology deals in part with the stratigraphy and structure of the rock formations that make up the earth's crust. These geologic formations constitute the framework through which ground water moves or is barred from movement. A formation, or rock material, that will yield water in sufficient quantity to be of consequence as a source of supply is called an *aquifer*, or simply a water-bearing formation, which is one that contains gravity ground water.

Nature provides a rather complete gradation from highly permeable materials which, if saturated, are very productive aquifers, to impermeable materials that yield practically no water. Thus a classification of rock materials merely as permeable or impermeable is in most places an oversimplification of the actual conditions. Indeed a formation classed as an aquifer in a region nearly destitute of available water might be viewed as unworthy of the name in regions where very large supplies can be obtained from wells tapping other formations. The term *aquifer* is sometimes used to designate individual water-bearing beds, perhaps only a few feet thick, and sometimes to designate thick series of beds of varying permeability, where the individual beds are more or less interconnected hydraulically.

The term *ground-water reservoir* also has rather flexible usage. Commonly it is used interchangeably with *aquifer*. More broadly it may represent the water-bearing materials in an extensive area, as for example the San Joaquin Valley ground-water reservoir in California, which supplies about a quarter of all the water pumped from wells in the Nation. Still more loosely the term has been used to designate all the rock material of a continent, but such loose usage must ignore the contrasts in permeability and the resulting contrasts in capabilities as to ground-water storage and development.

Great variations in permeability of rock materials have been chiefly responsible for the considerable variation in occurrence of water in the ground-water reservoirs of the continent. In some areas not only the ground-water reservoir but the materials above it are all relatively permeable, although some variation is almost inevitable. Wells dug or drilled in these areas commonly penetrate first some dry strata, then materials that are increasingly moist (the *capillary fringe*), and then materials from which water enters the well—thus they have gone through the zone of aeration

and reached the zone of saturation. The top of the zone of saturation, the *water table*, rises as water enters the ground-water reservoir, and falls as water drains away to lower parts of the reservoir or as it is discharged by wells or other means. This water is *unconfined*.

Relatively impermeable layers within the zone of aeration produce various complications in this simple picture. Such layers may be right at the surface, so that there can be very little infiltration, and practically all the water from precipitation must collect on the surface or run off overland. Impermeable material may be present at various depths below the land surface, whether as hardpan within the soil zone, or clay or other tight material at greater depth. Such material may be poorly permeable and thus retard downward percolation, so that there is an accumulation of water and temporary saturation of material immediately above it. Or it may be impermeable enough to prevent downward percolation, so that a ground-water reservoir is permanently maintained above the impermeable zone. Such bodies of ground water within the zone of aeration are *perched*. Many are of very small extent, and may disappear in a short time after rains. Some perched ground-water reservoirs yield water to wells and springs and are thus of some economic value, but they are of very minor importance in the Nation's over-all water economy.

Many deep wells penetrate far into the zone of saturation, and go through rock materials that range widely in their permeability. As these wells are being drilled, water may rise markedly above the top of the aquifer that is being tapped, and may even overflow at the surface. Such water is *confined* beneath less permeable material.[1] If the water in the aquifer is under sufficient pressure to rise above the zone of saturation it is *artesian*, and the aquifer is then an artesian reservoir.

An artesian reservoir does not receive any water by downward movement through the confining bed that overlies it: even if the confining bed were moderately permeable, the artesian pressures would oppose such movement. An artesian reservoir as a rule therefore is replenished in some area where the confining bed does not exist, and where ground water is under water-table conditions. Thus, although it is important to differentiate between confined and unconfined waters—because of the differences in ground-water hydraulics—it should be recognized that an "artesian reservoir" is actually only a part of the complete underground system necessary for yielding perennial supplies to wells or springs. For artesian aquifers, as well as for other ground-water reservoirs, there must be some area in which the soil or other surficial material, and any underlying unsaturated material, are sufficiently permeable to permit water to enter the aquifer. Such areas are the *recharge areas* for ground-water reservoirs—the areas in which replenishment occurs.[2]

[1] It is not necessary that the confining bed be impermeable, but only that it be less permeable than the aquifer. Thus the Dakota sandstone in North and South Dakota is a famous artesian aquifer in which water is confined beneath dense shale. At the base of the Wasatch Range in Utah there are beds of loose sand more permeable than the Dakota sandstone; nevertheless that sand constitutes the confining bed above coarse gravel, from which water flows by artesian pressure. In both instances, water moves far more easily through the aquifer tapped by wells than through the overlying beds.

Storage and Perennial Yield

The familiar term *reservoir* as applied to storage of surface water can be just as well applied to underground storage. Both types of reservoirs serve the same general purpose for mankind, in that they tend to smooth out the very great daily, seasonal, and annual fluctuations in the amount of water supplied by precipitation. Construction of surface reservoirs has enabled man to reduce flood crests and the possible damage to property, and to store water for release as needed in municipalities or industries or power plants or irrigation districts or navigable streams. Nature has provided ground-water reservoirs which similarly absorb water chiefly during periods of surplus, and release it gradually to springs or other avenues of discharge. Ground-water reservoirs are the source of most of the stream flow that is sustained during rainless periods. The Nation's subterranean reservoirs range from those of limited extent that hold relatively little water, to those that extend over thousands of square miles and hold many times more water than can be stored in the largest developed surface reservoirs.

The amount of storage in a ground-water reservoir is no indication of that reservoir's capabilities for sustained yield of water to wells and springs. The limit of perennial yield is set by the average annual recharge to the reservoir, just as the useful yield of a surface reservoir is set by the inflow to it. Some small ground-water reservoirs along streams are capable of a large sustained yield because they are readily recharged from the stream; others, notably in desert areas, may be far larger and hold vast quantities of water in storage, but yet have very low capabilities for perennial yield because of meager recharge. As an example, the ground-water reservoir under a 6,700 square-mile area in the Southern High Plains of Texas is estimated to hold more than five times as much water as Lake Mead (formed by Hoover Dam), but its annual recharge is less than one-half of 1 percent of the annual inflow to Lake Mead.

Characteristically there is natural movement of water through ground-water reservoirs, but that movement is at snail's pace. Whereas stream velocities are commonly quoted in terms of feet per second, ground-water velocities are measured in feet per day, or even feet per year. The ground water moves from recharge areas to areas of natural discharge, and through the years the average replenishment to the reservoir is equivalent to the average discharge. Wells

[2] Confined water has also been encountered in wells in many parts of the country, particularly in oil fields, under conditions that indicate that it has been isolated from other waters, and in many instances that it has been trapped there for geologic ages. These trapped waters generally are highly mineralized and not usable, but some are suitable for some uses, such as the brines that provide various chemicals, as in Michigan and West Virginia. Trapped waters are found under conditions analogous to those requisite for petroleum accumulation, and they are similar to petroleum resources in another respect: being isolated from the natural circulating system of the hydrologic cycle, they are not renewable or replenishable as are most water resources.

intercept some of the water along its route, and if their yield is sustained year after year, it is because the water drawn by them is replaced by increased recharge, or is diverted from its course toward ultimate natural discharge. As a rule, water will not remain under a piece of property until the owner is ready to use it: eventually it will be discharged from the ground-water reservoir whether he takes it out or not. In other words, conservation of ground water is not necessarily achieved by not using it.

The velocity of ground-water movement is an important factor determining the sustained yield of wells, for that yield is limited to the quantity of water that moves to the well from the places where the water entered the ground. Wells remote from a source of replenishment cannot yield water perennially at rates greater than it moves through the aquifer, even though the quantity available at the source is many times as great. Artesian supplies in particular are limited by this factor of *transmissivity* of the aquifer, and many of the Nation's problems of "failing water supplies" stem from this limitation. The problems are analogous to those of a town that has an adequate over-all water supply, but has distribution lines too small to carry the water needed in some parts of the town.

From the above discussion some guides may be offered for the effective development of underground storage for perennial use. The sustained yield of a ground-water reservoir (using the term to describe an underground unit of the hydrologic cycle, with its areas of recharge and discharge) cannot be greater than the average recharge, whether that recharge occurs by natural or artificial means; and generally the quantity recovered from the entire reservoir for use will be appreciably less than that inflow, because of the practical limitations of the recovery techniques. In any part of the reservoir—even at any particular well—a further limitation is imposed by the rate at which water can be transmitted through the aquifer; this limitation applies least to wells within the recharge area, where they can reap the benefit of any inflow in short order. These limitations are an oversimplification of a complex problem, and are only the hydrologic limitations. In many areas economic, social, or legal factors limit the yield of ground-water reservoirs to a level far below their hydrologic capabilities.

The relation between recharge and sustained yield of ground-water reservoirs is so closely analogous to that between inflow and yield of surface reservoirs, that one may wonder why ground-water-development programs are not based on a knowledge of the recharge comparable to the knowledge of stream flow that we consider to be prerequisite to river-basin development. Part of the answer may lie in the fact that developed surface storage is a product of man's ingenuity and does not exist until he has made a substantial investment in labor and materials; whereas the ground-water reservoir is developed and filled by Nature, and lies ready to yield water for a small investment in well drilling. At any rate, "ground-water shortages" have been reported in areas in nearly every State, and in most cases the difficulties could have been avoided if the hydrology of the ground-water reservoir had been known.

In recent years there has been increasing awareness of this need for more knowledge concerning ground-water reservoirs. Studies are in progress in most States, especially in areas where crises have occurred or have seemed to be imminent. As a result of such investigations, some overdeveloped ground-water reservoirs have been put on a sustained-yield basis, either by limitations on development or by supplementing the natural recharge by artificial means. And in many places sound programs for development have been formulated on the basis of the findings of these scientific studies.

In extensive areas the surficial materials are permeable but unsaturated, and in some places such materials may extend to depths of several hundred feet. These do not come within the definition of "aquifers" or "ground-water reservoirs," which are limited to saturated rocks. But they can be classed as potential underground-reservoir sites, which may be placed in service if suitable methods can be found for saturating those materials. Indeed, there are already ground-water reservoirs in the irrigated areas of the West that once were composed of unsaturated rocks, but that now receive the excess water from irrigation, store it, and subsequently release it to wells and springs. There are also unsaturated rocks that will probably never provide satisfactory reservoirs, even though they are exceedingly permeable, because the materials are in places where water would drain out as fast as it could be added practically.

Infiltration vs. Runoff

The preceding sections have been devoted chiefly to a discussion of the principles of occurrence of ground water, and of the characteristics of ground-water reservoirs as they pertain to storage and yield of water. If man is to make best use of natural storage facilities, he must first know what those facilities are, and how they are maintained by Nature. With this fundamental knowledge, the development can be planned so as to achieve the greatest benefit from the natural facilities, and to supplement those facilities by artificial means where feasible.

Some attention has been given also to the capabilities of ground-water reservoirs for perennial or sustained yield. This leads to the important concept of ground water as a *renewable* resource. Practically all ground-water reservoirs are units of a natural circulatory system. Water is evaporated especially from the water surfaces of the earth, carried in the atmosphere, and eventually dropped as rain or snow. Precipitation upon the continents replenishes the water supplies in streams, reservoirs, and lakes, as well as in ground-water reservoirs. The natural circulation, the *hydrologic cycle*, is completed by flow of water from the continents to the oceans, or by evaporation of water from the continental masses.

The land surface is of critical importance in the hydrologic cycle, for it is there that the water from precipitation is divided into (1) particles that are absorbed by the earth and become subterranean water; (2) particles that remain upon the surface to form ponds or to run off overland; and (3) the few particles that are returned immediately to the atmosphere by evaporation. The absorption of water into the earth is called infiltration.

As already pointed out, the capability of a ground-water reservoir for sustained yield is determined by the quantity of inflow to that reservoir in its recharge area, where water can enter the reservoir by downward percolation from the land surface through permeable materials. To the users of the ground-water reservoir, infiltration *in those recharge areas* is of critical importance, and the identification and delineation of those recharge areas is an important step in any efforts devoted toward improving the natural facilities for ground-water replenishment. (In view of the limited rate at which water can move through some aquifers, improving these natural recharge facilities may not enhance the yield of individual wells, however.)

Within the recharge area, the ground-water recharge as a rule is only a fraction of the total infiltration. The soil absorbs water until it has reached its capacity for holding water by molecular attraction, and only then does water start to move on downward to the ground-water reservoir. In the intervals between storms the soil moisture is depleted by evaporation and transpiration, and this depletion must be made up during subsequent storms before there can be additional downward percolation.

Infiltration depends upon climatic factors such as temperature and amount and intensity of precipitation; physiographic factors such as elevation and slope of the land surface, and permeability as determined by rock characteristics and as modified by plant material or the work of animal organisms. These factors may modify the total infiltration either by changing the permeability and, therefore, the rate at which water moves through the earth material, or by changing the time interval in which infiltration can occur.

Climatic Factors

The intensity of precipitation obviously is important in determining the proportions of infiltration and runoff. A soaking rain may be entirely absorbed by the ground, whereas a bouncing rain on the same area may form pools and rivulets. In large part the difference is in the time allowed for infiltration, but recent studies show also that the impact of hard rains reduces the infiltration capacity of some surfaces.

Temperature, because of its relation to viscosity of water, is an element that affects all rates of infiltration. The most obvious changes in infiltration, however, are noted when temperatures drop below freezing. Frost in the soil may impede infiltration and increase the proportion of runoff correspondingly. On the other hand, if, as is common in forests, snow accumulates upon porous soil that is not rendered impermeable by frost, the rate of snowmelt is slow enough to permit a high proportion of the water to infiltrate into the ground.

Physiographic Factors

The slope of the land surface is an important factor determining the proportions of infiltration and runoff. On a flat surface where there is no opportunity for runoff, the water may linger until the ground can absorb it. With increasing steepness of slope the impelling force of gravity becomes more encouraging for runoff. Thus runoff may be far greater on a steep slope than on a gentle slope having a soil of equivalent permeability. Man has been able to increase the infiltration into soils on sloping surfaces by modifying those slopes. Terraces, contour trenches, and similar structures are designed to delay the runoff and thus increase the length of time for infiltration.

The altitude of the land surface may also be a factor in infiltration, chiefly because of its effect upon the climatic factors of precipitation and temperature, and upon the factors of vegetation and soil development.

Mantle-Rock Factors

Mantle rock is the geologist's term for the loose rock materials that mantle the earth's surface. It includes the parent material of the soils that cover practically all the continent. But in soil development the parent material may be modified extremely; so that the soil is a product also of the action of plants and animals and man, of climatic conditions, and of the time during which these agencies have been at work.

The parent material may be decayed rock or detritus of a wide variety of textures, and may thus vary widely in permeability. Whatever the permeability of the parent material, it is likely to be modified extensively by soil-development processes. Vegetation produces organic matter, or *humus*, in the zone that roots can penetrate, and if the parent material was fine-textured its permeability is likely to increase because of this organic matter. Worm borings and animal burrows also may increase the permeability. On the other hand, soluble mineral matter may be leached, and clay particles washed, from the surficial materials and redeposited at somewhat greater depth, where a zone of relative impermeability may result. The ultimate of soil development in humid climates is the breakdown of particles to minute size, the removal of all mineral matter except the insoluble iron and aluminous residues, and thus the accumulation of a relatively impermeable (*lateritic*) soil. Such soils develop very slowly in temperate latitudes and are not likely to develop where appreciable erosion is occurring; they are rare in the United States today.

Infiltration is commonly greater, and runoff less, from areas covered by vegetation than from bare areas of similar soils, slopes, and climatic conditions. For good reason, then, vegetal cover has been successfully used as a corrective measure in some areas of excessive erosion by running water. But this vegetal cover uses water, and inevitably some of the water that infiltrates into the soil is returned to the atmosphere by transpiration.

In the recharge area of a ground-water reservoir, the infiltration may be greater if there is a vegetal cover than if no vegetation were present. But, because the recharge to the reservoir is limited to the quantity that percolates downward from the soil zone, the beneficial effect of vegetation would be measured not by the increased infiltration but by the difference between increase in infiltration and increase in transpiration and interception. Experiments in artificial recharge using water from streams have shown that, in some areas at least, a vegetal cover resulted in increased infiltration far exceeding the quantities of water used by the plants. Thus, the vegetation was instrumental in augmenting the recharge to the ground-water reservoir. The relation of various types of vegetal cover to ground-water recharge under various climatic conditions needs far more research before the fundamental principles can be well established.

Principal Types of Aquifers

As a general rule, the delineation of aquifers is a delineation of rock types, for the classification of rocks as sedimentary, metamorphic, or igneous, or as loose or consolidated, or as soluble or insoluble, quickly reveals some of their characteristics with respect to the occurrence of ground water. An orderly description of the geology and geologic history of any region goes much further than mere segregation of rock types, for it involves the identification and grouping of geologic formations in order of age, and the changes wrought by various forces upon those rocks. As the occurrence of ground water is governed by this geologic framework, a knowledge of the basic geology is also essential for an orderly discussion of ground-water conditions.

The lack of any reference to geologic age in the following discussion is not intended in the least to minimize the importance of comprehensive geologic data in ground-water studies. But cavernous limestones in Florida, Tennessee, New Mexico, Texas, and Utah are aquifers having many characteristics in common, although they are far apart in age. Loose sand deposited yesterday by the Mississippi River may be similar in water-bearing properties to loose sand deposited 500 million years ago. The only generalization that can be made relating aquifers to geologic age is that the younger rocks are likely to be the more important aquifers, because they have had less time for consolidation and less opportunity to be deeply buried.

A geologist's description of a rock generally includes all the features that can be observed by the naked eye as well as by microscopic examination. Inevitably some of these features will pertain to the pore spaces, or the water-soluble constituents, or other characteristics of special interest to the ground-water hydrologist. On the other hand, the geologist and the ground-water hydrologist emphasize, respectively, the doughnut and the hole, and it is to be expected that their selection of the salient features concerning any specific rock will differ somewhat.

Perhaps the greatest difference in emphasis is in the loose gravel, sand, and clay which mantle the surface of the earth nearly everywhere, and which may extend to depths of hundreds or even thousands of feet. These are the least likely places to look for economic deposits of most mineral resources. But they are far and away the most important producers of ground water. Probably more than 90 percent of all wells do not reach bedrock, and a similar proportion of all water pumped comes from unconsolidated rocks, chiefly gravel and sand. Our knowledge of ground-water occurrence also is most comprehensive in these unconsolidated materials.

Gravel and Sand

Most of the water pumped from wells in the United States comes from aquifers of loose gravel and sand. The five States of California, Arizona, Texas, Arkansas, and Louisiana alone pump more than two-thirds of all the water taken from wells throughout the Nation, and nearly all that water is drawn from unconsolidated beds of gravel and sand. The types of occurrence of these aquifers may be broadly grouped as (1) watercourses, (2) abandoned or buried valleys, (3) plains, and (4) intermontane valleys.

Watercourses.—Watercourses are hydrologic units that include both surface water and ground water; that is, the water in a stream channel plus the ground water in the alluvium that underlies the channel and forms the bordering flood plains. Large quantities of ground water are pumped from watercourses, especially in the industrial areas of the East and Midwest. Many wells are so situated that the water pumped from them is readily replaced by infiltration from the river, and their yield is exceptionally large. High permeability of the aquifer throughout the route from the river channel to the well is a prerequisite for successful wells. Watercourses may offer excellent opportunities for large ground-water supplies at some places, whereas at other places the alluvium is predominantly of fine texture and will yield only meager supplies.

Abandoned or buried valleys.—These valleys are no longer occupied by the stream that formed them. Some alluvial-channel deposits have an extent, thickness, and permeability far greater than the present stream could possibly produce; and some valley deposits have been buried so that they no longer form any part of the present drainage system. Although the abandoned or buried valley may resemble a watercourse in permeability of materials and in quantity of

ground-water storage, the recharge and, therefore, the capabilities for perennial yield are likely to be far less.

Many ancient stream valleys were buried or abandoned during the Ice Age, when huge glaciers developed in Canada and advanced into the northern part of the United States. Buried and abandoned valleys are now numerous in those glaciated areas, and in the valleys of streams that once drained the ice fronts.

Plains.—In the part of the United States east of the Rockies there are extensive plains which are underlain by unconsolidated sediments. Sand and gravel beds from important aquifers under these plains in some places; they are relatively thin and not very productive in other places. These plains flank the highlands or other features that were the source of their sedimentary deposits. Thus the Great Plains border the Rocky Mountains, and important aquifers of stream-deposited gravel and sand beneath the plains occupy a broad belt from Texas to South Dakota. The glacial-drift plain and associated outwash plains of the Northeastern States mark the approximate limits of the vast glaciers that have occupied that area. The Coastal Plain along the Atlantic and Gulf coasts has marked the edge of the continent, and the strata are partly marine and partly fluviatile in origin. The ground-water reservoirs under all these plains are recharged chiefly in areas where they are accessible to downward percolation of water from precipitation and, in some places, from streams.

Intermontane valleys.—The intermontane valleys of the West are similar to the Great Plains in that they are underlain by a tremendous volume of unconsolidated rock materials derived by erosion of mountains. However, those materials are in a host of more or less separate basins bordered by mountain ranges. These numerous projecting mountain ranges give the western country an appearance far different from the plains areas of the East.

Sand and gravel beds are the aquifers in the intermontane valleys, and are of outstanding economic importance because they alone produce more than half of all the water pumped from wells throughout the Nation. There is some recharge by infiltration of precipitation, but as a rule the ground-water reservoirs are replenished chiefly by seepage from streams into the alluvial fans at the mouths of their mountain canyons. The storage in many of these reservoirs is very large in comparison to the meager annual recharge that is available in these arid regions.

Limestone and Other Soluble Rocks

Limestone and dolomite, composed dominantly of calcium and magnesium carbonates, constitute between 5 and 10 percent of all sedimentary rocks. They vary widely in permeability. Some are relatively dense; others have appreciable porosity, from the initial interconnecting pore space that remains in incompletely consolidated rocks; many have developed permeable zones subsequent to their deposition.

The limestones that are most important as ground-water reservoirs are those in which a sizable proportion of the original rock has been dissolved and removed. These limestones have the largest "pores" of any rocks: caverns large enough to admit a man and subterranean channels that carry the entire flow of a stream (in common parlance, a "lost river") for several miles. Many very large springs issue from limestones; of the 65 or more springs in the United States having a maximum discharge of more than 100 cubic feet a second, more than one-third originate in limestone.

The solubility of calcium carbonate in water is the factor that sets limestones apart from all other common rock types as ground-water reservoirs. Most of the rocks forming ground-water reservoirs may be regarded as static; in limestone reservoirs the rock itself plays a dynamic part, because of its solubility. Limestones are exceptional among consolidated rocks also, in that they commonly develop increased permeability in time.

Most limestones are of marine origin, and many are composed largely of the fossil remains of marine organisms. If fresh water now occurs in any of these beds—that is, if the beds constitute a usable ground-water reservoir—the sea water must have been flushed out, and water from rain and snow must have circulated through the rock. In other words, the formation has been incorporated into the hydrologic cycle.

In soluble limestone, the hydrologic cycle is a vicious cycle insofar as solidity of rock is concerned, but an excellent developer of ground-water reservoir capacity. In regions where limestone forms the land surface and extends to considerable depth, the infiltration from rainfall and the subterranean movement of water provide opportunities for solution of the calcium carbonate, and waters from limestone are prevailingly hard because of this dissolved mineral matter. By dissolving the rock, greater pore space and permeability are achieved, so that a progressively greater proportion of the precipitation can follow the underground circuit.

The ultimate development of limestone terranes is a *karst* region in which most of the drainage is subterranean, and the limestone contains ground-water reservoirs of large capacity. Common features of such regions are caves, sinkholes, "lost rivers," large springs, interior drainage of large areas, and in some places surficial materials too permeable to hold water and therefore sparsely covered by vegetation. Notable limestone terranes are to be found in central Tennessee, in the Shenandoah Valley of Virginia, and on the Florida Peninsula. Similar solvent action in past geologic ages is probably responsible for the great permeability of limestones in many other States, notably in New Mexico and Missouri.

The solution cavities and channels in limestone may be large enough that wells reaching them are very productive. On the other hand, the rapid flow through limestone may be a health hazard if the water is polluted before it enters the limestone or receives pollution thereafter. The solution

channels may be separated by considerable amounts of solid rock, so that some wells may penetrate deep into limestone without yielding water, even though productive wells are close by. And wells going deeper than the zone of ground-water circulation are likely to encounter saline water, and perhaps rocks of low porosity. The ground-water hydrology of limestones, and particularly the factors that control the development of permeability, will need far more study before they are thoroughly understood.

Gypsum is another soluble rock that may develop sufficient permeability to be classed as an aquifer. It is not a common rock, and few water-bearing gypsiferous rocks have been developed for use. In the Duke area in western Oklahoma, water is pumped from gypsiferous beds for irrigation; the water is hard and high in sulfate, but usable nevertheless. Rock salt is also sufficiently soluble to develop a high permeability, but the water discharged from such beds is too saline for most uses. Openings in salt and gypsum at any appreciable depth, in contrast to those in limestone, generally close by plastic flow because of the relative weakness of the salt and the weight of the overburden.

Basalt and Other Volcanic Rocks

Basalt, a dark-colored volcanic rock that may spread in sheets to form extensive plains, has probably about the same range of permeability as limestone. In general the basalt flows themselves are very permeable, except for the massive flows. Other permeable zones in these volcanic rocks include flow breccias, porous zones between successive lava beds, lava tubes, shrinkage cracks, and joints. More than half of the largest springs in the United States rise in basalt or in gravel laid down in valleys cut into the basalt. Many wells in basalt are excellent producers with little draw-down, and their yield is sustained year after year. Yields of 500 to 2,000 gallons per minute are common.

The materials underlying basalt plains in many parts of the western United States are sufficiently permeable that the water table is very flat. Variations in permeability, however, are shown by the effects of irrigation of basaltic lands along the Snake River in Idaho. Near Twin Falls the water table in 1905 was probably more than 200 feet deep under most of the area, but it rose several feet a year as water from the Snake River was used to irrigate the land; by 1928 many areas had become waterlogged, and drains and tunnels had been constructed to keep the water table down. It is estimated that about 6,000,000 acre-feet was added to permanent ground-water storage between 1905 and 1928. In contrast, the water table north of the river has risen only a few feet since irrigation began, although about 600,000 acre-feet of surface water is applied each year. There the basaltic materials are so permeable that water moves readily westward, and appears as increased spring discharge along the banks of the Snake River.

Other volcanic rocks, notably the rhyolites, are generally less permeable than basalt. Shallow intrusive rocks, such as dikes, sills, and plugs, have low permeability, and most of them are practically impermeable. Thus they act chiefly to interrupt the flow of water in permeable rocks cut by them.

Sandstone and Conglomerate

Sandstone and conglomerate are the consolidated equivalents of sand and gravel, and differ from them chiefly in the presence of cementing materials between the grains or pebbles. The porosity has been reduced by the cement, and many of the more indurated rocks are too thoroughly cemented to yield much water from the original openings between their grains. In quartzites (the metamorphic rock derived from sandstone and properly included in the following group) these interstices have been almost completely closed by cementation, and ground water, if any, percolates through the joints by which the rock is broken.

The best-known sandstone aquifers are only partly cemented, and are believed to yield most of their water from pores between the grains, although fractures may serve to collect the water from the smaller pores. Many sandstones are thoroughly cemented, and yield water wholly through joints. A moderate amount of cementation may improve a sand, so far as wells are concerned, by making it coherent and less likely to run into the wells. A good well in sandstone may yield a few hundred gallons a minute, but as a rule sandstone wells furnish distinctly less water than wells supplied by unconsolidated gravel and sand. Because of the generally small pores, water is transmitted slowly through sandstones; where water occurs under artesian conditions, the artesian pressure may decline rapidly as the water is released through wells. Conglomerates are not important aquifers, partly because of their limited distribution.

Crystalline and Metamorphic Rocks

The crystalline and metamorphic rocks occur chiefly in mountainous areas, or in areas that have been mountainous in past geologic ages. As a rule they are poor water bearers, and where they are buried beneath several hundred feet of other rocks they are not likely to yield enough water for even a domestic well.

Where these rocks are close to the surface in humid regions, they yield small but reliable water supplies to many wells. The limiting depths for ground-water development in them are not great. Water occurs in the somewhat decayed rocks near the surface, and this zone may extend to depths as great as 100 feet. Drilled wells may obtain water from joints or shear planes at greater depth, but it is generally not worth while to drill deeper than 300 feet. Most wells in these rocks yield supplies sufficient only for domestic use, and a yield of 100 gallons per minute may be considered large.

Porous but Poorly Permeable Materials

Clay, clay mixed with coarser materials, shale, silt, glacial till, weathered residual rocks, torrential stream deposits, and poorly sorted alluvium are generally porous, but their pores are so small that the materials are relatively impermeable. These are the rock materials that can retain much water by molecular attraction. Many of them make excellent soils, and most of the soils of the Nation are properly included in this group.

Generally these porous materials would not be listed among aquifers at all. Where there are productive aquifers, these poor producers may act as confining beds or as barriers to ground-water movement. They are mentioned because they are near the surface over very extensive areas of the United States, and because they furnish small supplies to many thousand wells. They are, therefore, an important source of water for millions, particularly of the rural population.

Many of these porous materials are permeable enough to permit very slow drainage of water from them. One type of development that was well suited to this low permeability was the dug well which penetrated several feet into the saturated material, and which served the limited needs of a farm dwelling without modern plumbing. The well itself stored several bucketfuls of water, and when the day's supply was withdrawn and carried to the house, that water was replaced in the next several hours by drainage into the well. Many owners of such wells, after installing a pressure pump to serve modern home facilities, have found that the well no longer yields a supply adequate for their needs.

Characteristics of Major Ground-Water Regions

General Statement

THE FOLLOWING SECTIONS outline the general hydrologic conditions and the facilities for storage and use of ground water in 10 major divisions of the United States. (See fig. 1.) These regions are differentiated chiefly on the basis of the types of aquifers that are the dominant sources of ground water, but for some regions other hydrologic conditions also are important factors.

The classification of these regions gives no consideration to the significant factor of geologic age, and is therefore probably too simplified to receive the unqualified approval of most ground-water geologists. For a more comprehensive classification of the ground-water regions of the country, the reader is referred to Meinzer's summary of the occurrence of ground water, wherein the United States is divided into 21 ground-water provinces, based upon consideration of the several important groups of aquifers in the country, namely, glacial drift, valley fill of the western basins, Tertiary lava, Miocene and Pliocene formations of the interior, Cretaceous formations, Paleozoic sedimentary formations, and pre-Cambrian and other crystalline rocks (Meinzer, 1923, pp. 309–314). These 21 provinces have formed the basis for the classification used below, with several modifications because of the reduction to 10 divisions.

It is noteworthy that these ground-water regions do not conform to drainage basins. Nor do the provinces delimited by Meinzer generally correspond to drainage basins. The Columbia Plateau and the Colorado Plateaus are exceptional in that they are largely, though not entirely, within the basins respectively of the Columbia and Colorado Rivers. For the most part, each of the country's major streams drains several diverse and often quite contrasting regions, insofar as ground-water reservoirs are concerned. It follows that river-basin development as a general rule involves several areas of contrasting ground-water characteristics. Such complexities add to the difficulties of comprehensive planning.

The following sections are arranged more or less in order from west to east across the country. Brief summaries of the characteristics of each of the 10 regions are followed by a somewhat longer discussion of the outstanding features concerning the ground-water reservoirs in those regions. Several areas of ground-water development are discussed as examples, and references are made to published reports concerning those areas. Many other areas, mentioned briefly, are described in more detail in a recent publication by the author (Thomas, 1951).

FIGURE 1.—*Ten ground-water regions of the United States.*

Western Mountain Ranges

Summary

Some of the ranges are high; some are low. Some are large; some are small. Almost all are built of hard, dense, rather tight rocks, and are flanked by alluvium formed of their own erosional debris. The amount of precipitation they receive ranges from more than 100 to less than 10 inches, but all except the lowest, driest ones receive substantially more than the adjacent lowlands and are—or once were—covered with forest.

By virtue of their height, the mountains are the great rain catchers or water collectors of the West. Because of the tightness of the rocks of which they are built and of their rather thin mantle of weathered rock and soil, they do not store ground water in great quantity, or for long. Their main storage, again by virtue of their height, is in the form of snow.

The forests are there because the water is there—they do not create the water or cause the higher precipitation. Their function is to hold the soil on the steep slopes and to keep it open and permeable, so that the small underground storage capacity is used to fullest advantage in delaying and reducing flood peaks in time of heavy rainfall or rapid melting of snow. Where the forest cover is in good condition nearly every drop of water that reaches the streams travels at least a little way below the ground surface. Thus the ground-water reservoir, though thin and of small total capacity, is of great importance.

The mountain ranges are the source of floods which occur whenever the rainfall, or rate of snow melt, exceeds a certain value that is critical for the area concerned. Such floods cannot be prevented, except by controlling the meteorological conditions that produce them—a process not yet demonstrated to be practical. However, their number and their destructiveness can be reduced within certain limits if the condition of the soil both on the mountain slopes and in the valleys is maintained at maximum stability and infiltration capacity, so that the precipitation from smaller storms is absorbed by the soil. Nevertheless, storms of great intensity are capable of producing great floods that no acts of man can substantially influence. If the soil has been damaged by improper forest cutting, overgrazing, or bad mining practices, its natural infiltration capacity may have been decreased and storms of lesser intensity may then produce destructive floods. In this event, the mountain ranges will have become the source of sediment in excess of the amount produced by normal erosional processes, and this sediment may clog reservoirs and stream channels and cover fertile valley soil with sterile debris. On the other hand, where the native vegetation has been destroyed, the water it normally would use adds to the total water yield—including, in some cases, a greater amount that passes deep into the ground. However, we must measure the bad effect of floods and resultant excessive sediment against the benefits of an increased water crop.

Controlled revegetation of bare mountainsides where feasible, selecting the type of cover according to its monetary cost, its soil-holding properties, and the value of its economic or other use or product in relation to the amount of water it will use. Designing and building economical and effective flood-control or flood-protection structures. The goal is the restoration of the western mountains and their plant cover to the stage where they will yield the most water with the least sediment and with maximum protection of their beauty and their usefulness as a source of mineral and forest wealth, and as a refuge alike for wildlife and for the tired city dweller or flat-land habitue.

No one of the many fields of knowledge required for successful use of our mountains as sources of water is complete enough. Data on the amount of precipitation and on the way it occurs in relation to altitude and steepness and direction of slope; on the water yield in relation to kind of underlying rocks, slope, thickness of soil mantle, and kind of vegetation; on the erodibility of various soils and rocks and the soil-holding ability of different plants—these and many others are needed. As the principal sources of the West's water, the mountains must be the subject of more intense and coordinated hydrologic research than ever before.

This region includes the Sierra Nevada of California, the Cascades and Coast Ranges farther north, and the Rocky Mountains from Montana to New Mexico—essentially the highest and most extensive mountainous areas of the western half of the United States (fig. 2). The region is approximately equivalent to Meinzer's Pacific Mountain, Northern Rocky Mountain, and Southern Rocky Mountain ground-water provinces. It has a rough horseshoe shape, with one prong extending down the Pacific coast, the other following the Continental Divide through Colorado, with a spur into Utah.

The region has a considerable diversity of aquifers, whether considered as to type of rock, geologic age, quantity of water in storage, or capabilities for perennial yield of water sup-

plies. In comparison with other major ground-water regions, the western mountain ranges generally possess ground-water reservoirs either of limited extent or volume, or of relatively small yield. Indeed, the region abounds in the two groups of aquifers (crystalline rocks, and porous but poorly permeable materials) that are least likely to yield copiously to wells.

Topography and climate exert an influence upon ground-water conditions in the western mountain ranges that serves to discriminate them as a unit from adjacent areas (fig. 3). One feature that ties this attenuated region into a logical hydrologic unit is high annual precipitation. The two southern prongs, in California and in Colorado, are formed by the highest mountain ranges in the United States—ranges that reach skyward more than 14,000 feet and are able to collect copious quantities of water from the atmosphere. Farther north the crests of the ranges are lower, but the net water supplies from precipitation are generally at least as great, and in places far greater. On the western slopes of the Olympic Range in the northwest tip of Washington, the annual precipitation is the highest in the Nation.

The region is prevailingly rugged, and some of it is practically inaccessible. It is very sparsely populated, and most of the people are concentrated in the few valley areas, in mining districts, and in service towns for transcontinental railroads and highways. The total water supplies of the region are far greater than the needs of the small population.

If the region has more water than its population can put to beneficial use, however, it is surrounded by a tremendous "have-not" area that can use far more water than is provided

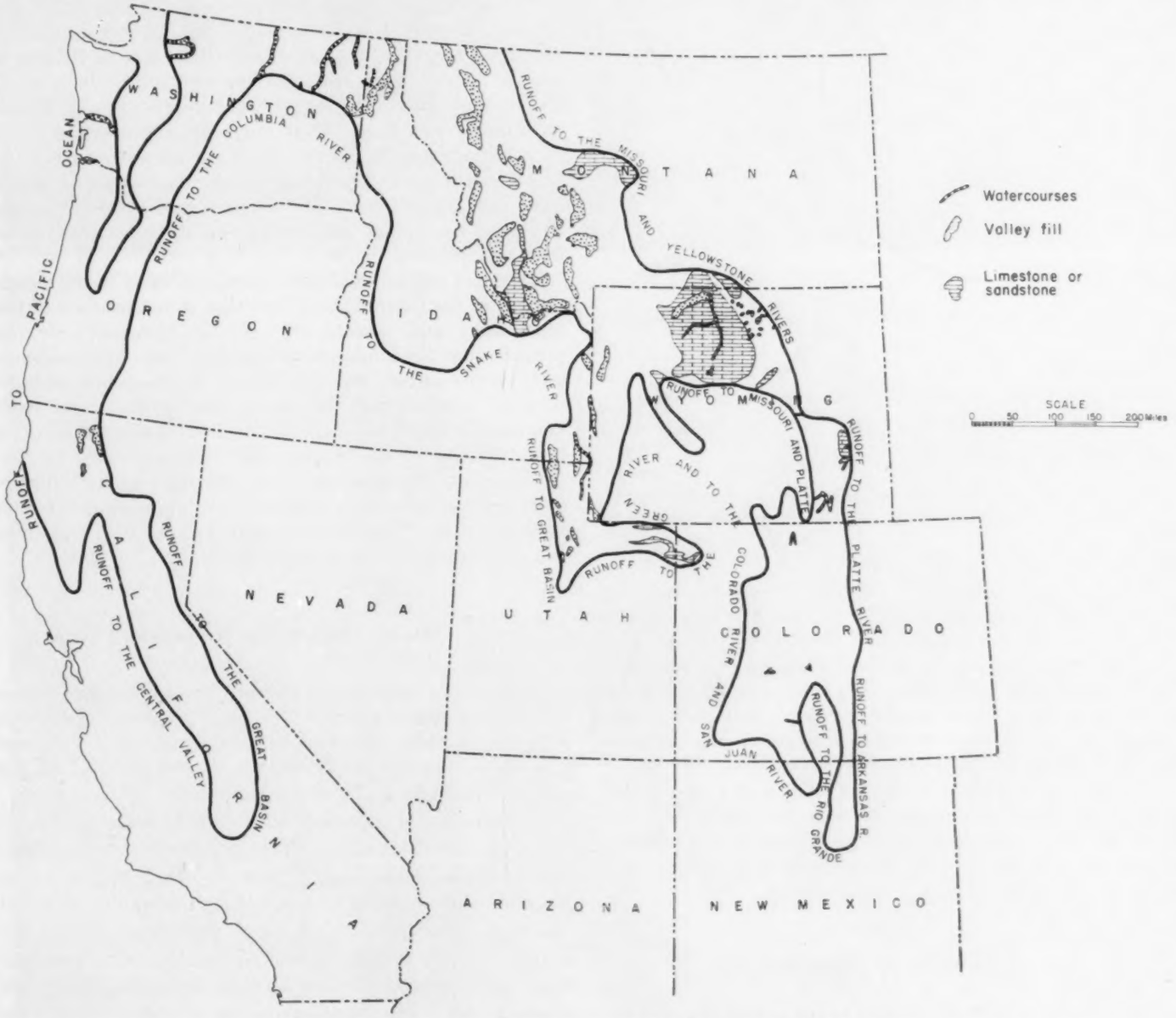

FIGURE 2.—*Western mountain ranges: snowsheds and water exporters of the west.*

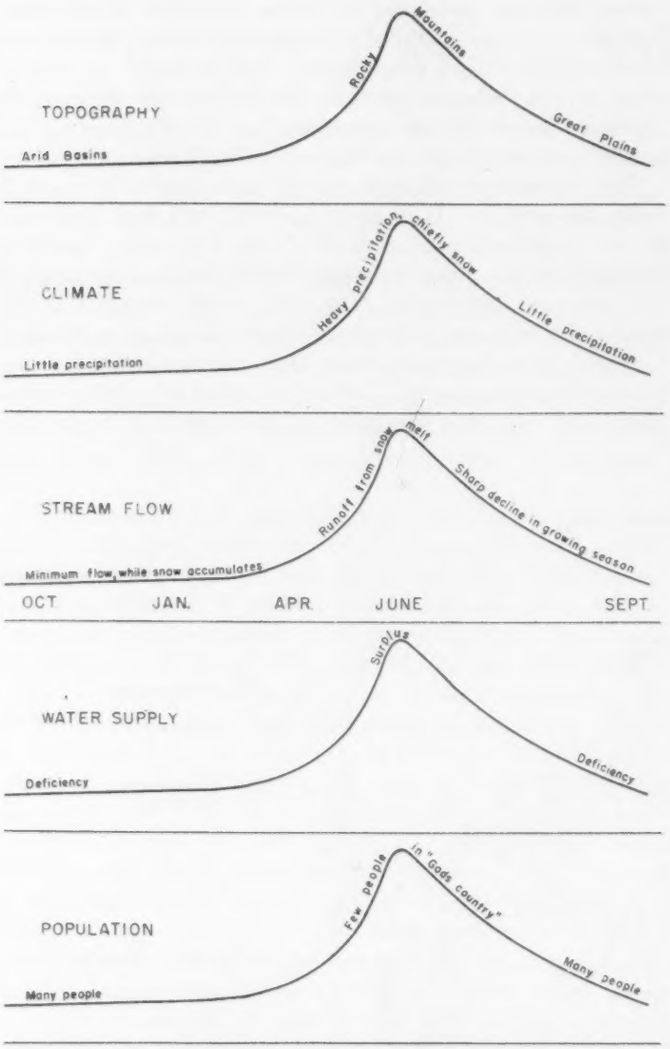

FIGURE 3.—*The ups and downs of the western mountain ranges.*

by the precipitation within it. Except for the western mountain ranges, practically all the western half of the United States is an area of water deficiency. The western mountain ranges export water to these thirsty areas, and the competition for that water has always been an outstanding feature in western history. The great rivers of the West originate in the western mountain ranges, and each is important in the economy of the arid parts of one or more States: the Sacramento-San Joaquin in California; the Snake in Idaho; the Columbia in Washington and Oregon; the Missouri in Montana and the Dakotas; the Platte in Colorado, Wyoming, and Nebraska; the Arkansas in Colorado and Kansas; the Rio Grande in Colorado, New Mexico, and Texas; the Colorado system in seven States.

The Importance of Water Storage

The distribution of precipitation is not in accordance with the needs of the areas that have developed and used the water from the western mountain ranges. On the Sierra Nevada in California, for example, the precipitation, falling almost exclusively during the winter, is entirely out of phase with the use of that water, which is primarily for irrigation during the other months of the year. In the Rockies, too, the seasonal precipitation is poorly adjusted to the needs of areas dependent upon the mountains as a source of water; during the growing season precipitation is generally less than could be used by the mountain vegetation alone. Furthermore, during that season the storms are commonly of short duration and may be quite intense. The storm runoff following such precipitation may cause damaging floods, and it does not fit irrigation, municipal, or power schedules, for those schedules require a sustained flow that can be achieved only by means of some form of storage.

The records of stream flow give some indication of the natural storage of water provided in the humid western mountain ranges. The minimum or base flow of streams is mostly derived from ground-water reservoirs. In most of the streams leaving the region, the minimum flow is far less than the average flow. Thus, only a small proportion of the total stream flow is derived from ground-water reservoirs. In other words, the ground-water reservoirs as a rule do not have sufficient capacity for effective regulation of stream discharge by storage and subsequent release of the water from precipitation (fig. 4).

The most important natural storage of water in the mountains is in the form of snow, and thus it is a product of the topography and climate (fig. 5). In high altitudes the precipitation for 4 months or longer in each year accumulates on the surface and contributes to stream flow as temperature rises during the spring and summer. In most mountain streams the bulk of the annual flow occurs in a freshet lasting several weeks, which supplies water for irrigation during the early part of the growing season. Numerous reservoirs have been constructed in the mountain region to supplement the natural storage, and to yield irrigation supplies throughout the growing season.

The Ground-Water Reservoirs

Most of the rocks in the western mountain-range region are igneous rocks, metamorphic rocks, and well-indurated sedimentary rocks. Such rocks are characteristic of regions that have experienced the heat and pressure, the folding and deformation, that produces mountains.

In the extensive areas underlain by these well-consolidated rocks, ground water occurs either in the weathered material and overlying loose mantle near the land surface or at greater depths in joints and other fractures, fault zones, and the like. The fracture types of openings constitute the sources of water in wells drilled into the solid rocks; generally these wells yield only small supplies, sufficient perhaps for domestic use. The fractures are also a source of water for perennial springs, many of which have a relatively constant

FIGURE 4.—*The San Luis Rey River near Fallbrook, Calif. (Above and below) Before and after the floods of January, 1916. The excessive runoff eroded the mountainside in several places, and piled debris in the valley. (Photo by O. E. Meinzer, U. S. Geological Survey.)*

FIGURE 5.—*Snow on the Wasatch Range will provide water for irrigation of this field and orchard in Utah Valley, Utah.*

rate of flow. Such springs are most common in the canyons and other low parts of the prevailingly rugged region.

The surficial zone of loose mantle and underlying weathered bedrock is a ground-water reservoir of some importance, but the degree of that importance is a matter of diverging opinion. At opposite extremes, perhaps, are the overemphasizers who see the vast areal extent, but not the shallow depth as compared with ground-water reservoirs in other regions; and the underemphasizers who see the shallow depth but not the total volume that is involved in areas of thousands of square miles. Actually the term "ground-water reservoir" can be applied in a regional sense only if it is recognized as a composite of many units that have over-all similarity but individual diversity. Thus some may be delimited by outcrops of solid rock a few hundred feet apart; others by the divides between the stream basins to which they contribute. Some may be on elevated plains or on mountain meadows; others on steep slopes. Some may have a depth of a few feet; others several scores of feet, but rarely will the depth of mantle rock and weathered rock exceed a hundred feet. And within each unit there may be a wide range of permeability, depending upon the original rock and upon such factors as climate, topography, and vegetation.

Vegetation has made significant modifications in the permeability of this surficial material in the zone penetrated by roots. Practically all the western mountain ranges were once forested, and the region still has most of the forests of the West. Commonly, undisturbed forest soils are capable of absorbing water from snowmelt and even from moderately intense rainfall without runoff. Stream hydrographs suggest, however, that only a small part of this water is retained in ground-water reservoirs; at least in many areas much of it moves rapidly through the soil zone, as *subsurface storm runoff*, to enter streams within a few hours or days. Thus, organic soils are of especial value for detention of water that is quickly contributed without sediment to streams, and for storage of the soil moisture needed by vegetation.

Quantitative studies have not been made of the relation between the mountain ground-water reservoirs and stream flow. Our ignorance is partly due to the fact that the mountains, being practically uninhabited, are also practically devoid of wells, and wells are the periscopes through which the hydrologist must view the ground-water conditions.

Cavernous limestone is an important aquifer in some parts of the western mountain range ground-water region. In common with other sedimentary rocks the limestone beds are rather intensely folded in some ranges, where their upturned edges may be exposed. Such limestones form ground-water reservoirs that are the sources of large springs, of which those in the Uinta Mountains of northeastern Utah are examples. In a few places deep wells have tapped these aquifers in basin areas adjacent to the mountains, and have yielded water by artesian flow. The same formations may yield ground water in other areas where the possibilities have not yet been explored. The ground-water reservoirs in limestone, like those in the other consolidated rocks of the mountains, are but little known.

According to our present knowledge, the ground-water reservoirs having the best potentialities for development in the western mountain ranges are those in the loose gravel and sand of the intermontane valleys (fig. 7). Those reservoirs appear to have greater volume per square mile of land area, and greater yield per unit of volume, than the reservoirs in consolidated rock. Most of the sand and gravel has been deposited in the valleys by streams draining the tributary mountain areas. In the northern part of the region, however, the sand and gravel are partly of glacial origin. Particularly in the Puget Sound area, glacial outwash gravels form very productive aquifers.

The intermontane valleys in this region, particularly those in western Montana, are similar in many respects to those in the arid-basin region, discussed in the following section. Indeed, both regions are made up of mountain ranges and intervening valleys, and the distinction between the two regions is largely a matter of average altitudes, one having extensive high areas and few valley areas, and a more humid climate; the other having lower mountain ranges, more intermontane valleys, and a generally more arid climate. The boundary between the two regions is necessarily arbitrary, and even inconsistent in some places. Intermontane valleys

FIGURE 6.—*Well being dug in the Rhodes Valley, Utah. This small intermontane valley fill can yield far more water than will ever be needed from this domestic well.*

in Montana, being distant from the complex of desert basins in the Southwestern States, are included within the western mountain ranges. The San Luis Valley of southern Colorado, although surrounded by two of the highest ranges in the country, is grouped with other basins farther down the Rio Grande, in the arid-basin region.

Although the climate is arid enough to make irrigation necessary, the intermontane valleys of the western mountain-range region are well-watered in comparison to most arid basins, owing to inflow of streams draining the adjacent ranges. Because of the adequacy of surface water, there has been little impetus to explore the possibilities of pumping water from wells for irrigation. As a result, these ground-water reservoirs are not yet well known.

One result of lavish use of surface water for irrigation has been the waterlogging of fertile land. Helena Valley in Montana is an example. Its agricultural lands are largely dependent upon gravity diversions from streams for irrigation, and since irrigation began about 8,000 acres of fertile bottom land have been waterlogged. The valley is underlain by coarse gravel and sand which form a very productive ground-water reservoir. The reservoir is tapped by a few irrigation wells, and is capable of producing much larger quantities than are now developed. There is a good possibility that pumping from wells for irrigation of the lower part of the valley would lower the water table in water-logged areas, and also release surface-water supplies for use on lands higher on the slopes. However, an alternative plan of water development involves importation into the valley of enough additional water to irrigate 10,000 acres of new land and to supplement the water supply for another 15,000 acres of land, chiefly on the upper slopes of the valley. Such increased use of surface water might well increase the waterlogged area in the lower part of the valley.

Some intermontane-valley ground-water reservoirs are replenished by river infiltration, and if ground water were pumped from wells this rate of replenishment would doubtless be increased. The alluvium is probably thin in most places along the narrow valleys of perennial streams, but there may nevertheless be many localities where water can be pumped from wells in that alluvium, and then replenished from the streams.

Arid Basins

Summary

THE ARID BASINS are the alluvial basins that flank the mountain ranges of the West. They are filled with rock particles eroded from the mountains, and they receive their water from the same source. Typically arid, they are defined to include the Puget Sound region, the Willamette Valley, and other alluvial valleys of the Northwest which, though not truly arid, receive less precipitation than the adjacent mountains and are otherwise similar in hydrology to the more typical basins.

As the mountains are the great sources of water in the West, so the alluvial basins are the great receivers and storers of the water. They are of two main types—drained and undrained—but all receive, store, transmit, and discharge water, either by flow to streams that leave the basins or by evaporation and transpiration in broad dry lakes or *playas* in their lowest parts. Their underground storage capacity generally is many times their annual intake and discharge. The basins, the sites of the most productive soil of the West, are also a source of ground water for irrigation where surface water does not exist, or is already diverted. One important function of these ground-water reservoirs, made possible by their large storage capacity, is to serve as a source for increased withdrawal during periods of dry years when stream flow dwindles.

The ground water in many western basins is developed beyond its average rate of replenishment, and the stored ground water is being depleted. Unless supplemental water is provided, great agricultural developments such as those of southern California and Arizona are threatened with substantial reduction. Use of ground water is causing encroachment of salt water from the sea in places or from the lower, naturally salty parts of inland basins in others. In some areas the natural outflow that once carried off excess salt has been reduced so that salts are accumulating. Many areas lack adequate drainage and are waterlogged by excess irrigation.

In spite of the general scarcity of water in the West, millions of acre-feet of water are wasted each year by worthless vegetation or by direct evaporation, and other millions of acre-feet are discharged into the sea in floods. Through increased use of the underground reservoirs much of this water can be salvaged for man's use. By lowering the water table in the areas of evapotranspiration, much of the water now evaporated can be saved. By greater use of artificial recharge, much of the water that still runs off into the sea in floods can be stored in the ground. By drawing down the ground-water reservoirs in dry periods and refilling them in wet years, their storage capacity will be utilized more fully than under natural conditions, and the result will be greater recovery of the West's precious water and less damage by floods. Many waterlogged areas where the excess water is not too highly mineralized can be dried up by pumping from wells, and the water recovered can be reused for irrigation of desert tracts. As economic conditions permit, surplus water from wetter areas, such as the wet North Pacific coast, can be diverted to the drier areas.

We need to learn about the following subjects, among others: Principles of use of water by water-loving vegetation (phreatophytes): amounts of water used by various plants, under various climatic conditions, with different depths to the water table and different loads of dissolved mineral matter in the water. Amount by which evapotranspiration is reduced by lowering the water table. Methods, in addition to drawing down the water table, for eradicating phreatophytes. Principles of artificial recharge: efficiency of various infiltration structures or practices; treatment of infiltration areas to maintain or restore infiltration capacity. Study of well spacing and pumping techniques to achieve maximum desirable drawdown of the water table with least encroachment of salt water. Principles of economical pumping and drainage structures to reduce waterlogging. Engineering research on the most economical methods for long-distance diversion of water. In addition to these and other general studies, there is need for an exhaustive hydrologic-economic study of each basin to determine the specific practices that are needed and that can be paid for. No two basins are exactly alike, and specific methods devised for one cannot be applied to others indiscriminately.

This region (see fig. 7) includes the heavily populated part of California; the areas of interior drainage (known as the Great Basin) in California, Nevada, Oregon, Idaho, Utah, and Arizona; and the drainage basins of the Gila River and the Rio Grande in Arizona, New Mexico, and west Texas. This is the Southwestern Bolson ground-water province of Meinzer.

In addition, there is a "window" in the western mountain-range region, extending southward from Puget Sound through the Willamette Valley in Oregon. That lowland,

FIGURE 7.—*Arid basins (water budget based on low income but with vast ground-water reserves) include Puget Sound-Willamette Valley area, not truly arid but having many hydrologic features in common with the arid basins.*

though not truly arid, is much drier than the surrounding ranges, and is included within the region because irrigation, though not yet widely practiced, is generally desirable for maximum crop production.

The term "basin" may be misleading unless one realizes that a basin requires sides or walls to give it shape. The "arid basins" are bordered, and some are completely enclosed, by mountain ranges. There are probably more individual named ranges within the arid-basin region than in the western mountain-range region, but they are generally more isolated, smaller, and lower in crest. Mountains higher than 10,000 feet above sea level make up a very small proportion of the arid-basin region.

Although the region includes both mountains and valleys, the cities, towns, and cultivated lands are almost exclusively in the valley areas. Some of those valleys (such as Death Valley and Imperial Valley in California) are below sea level, and several are very little above. But the floors of most of the basins are a few thousands of feet above sea level, and would be called high by a midwesterner. Indeed, the San Luis Valley in Colorado is more than 7,000 feet above sea level, higher by far than most of the mountains of the East.

The arid basins are quite diverse in size and shape. What is called the smallest is a matter of definition as to the size of an area that is acceptable as a separate basin. The largest are the Central Valley in California, 350 miles from end to end, and the Great Salt Lake Basin in Utah, which has mountain ranges projecting as islands in midbasin. Some basins are completely enclosed and have no outlet; as in the kitchen utensils of the same name, water that drains from their sloping walls collects in the lowest parts. Others are valley plains along major streams, connected with or separated from (depending on the viewpoint) other similar plains by canyons cut through mountain ranges. Some are broad valleys open to the ocean, others drain into rivers that cut across them as well as across the adjacent mountain ranges.

There is also a considerable diversity of climate. Some basins never see snow; others may have a snow cover for several months each year. Some basins regularly achieve the highest summer temperatures in the Nation, others can count on subzero temperatures each winter. Some of the windiest and some of the calmest places in the country are within the arid-basin region. The precipitation ranges from less then 3 inches a year in several places to more than 20 times that amount near the coast of northern California, but most of the valley areas receive less than 15 inches annually.

One common climatic characteristic in all the arid basins is an inadequacy of precipitation during the growing season. Some California coastal basins have annual precipitation that would be adequate for agricultural needs, but unfortunately almost all of it falls during the winter. In the basins having a year-round growing season there is never enough precipitation in the valley to produce a crop. Thus, regardless of the combination of climatic factors, practically all basins are areas of water deficiency, insofar as local precipitation is concerned. There are several small areas suitable for dry farming, which depends upon storing available moisture in the soil zone, in the hope of achieving a successful crop at least 1 year in 3. By and large, however, the economy of the arid basins is founded upon the development and utilization of surface- or ground-water supplies, and the source of those supplies is very generally precipitation on some *catchment* area many miles from the cultivated land where the water is used.

The Importance of Importation of Water

In the West, "importation" commonly describes the water-development projects that require transportation of water from one drainage basin into another: basically, taking the water by pipeline or canal into an area that could not obtain it by natural flow in streams or underground. Los Angeles imports water from Owens Valley and from the Colorado River; San Francisco and Oakland obtain most of their supplies from the Sierra Nevada. Determination as to what constitutes an "importation" would require a decision as to what is a drainage basin. If the drainage-basin unit is only a few square miles in area, then a farmer may be importing water when he takes it in a ditch around the point of a ridge, although the distance from the stream source may be less than a mile.

So far as the individual water user in the arid basins is concerned, practically all his water for irrigation, domestic, or industrial use might be broadly regarded as "imported," unless his landholdings include an entire drainage basin, and unless he limits his use of water to the "water crop" of that basin. Typically the precipitation upon his land is inadequate for his needs. He must supplement his supply by obtaining either surface water or ground water, and he diverts that water through canals or wells from its course of natural flow. Thus the surface or ground water is generally imported into an area that would not be served by natural flow.

Throughout the arid-basin region, the natural water deficiency of the arable lands is recognized as characteristic and inevitable. Each man must look beyond his own farm for water that can supplement the precipitation on that farm. In most States in this region water rights are based on the doctrine of appropriation, which recognizes that the first user of water has the superior right for continued use, regardless of the place of his use with respect to the water source.

The arid-basin region adjoins the western mountain-range region in three major areas: around the prong of the Sierra Nevada in California, along the front of the Wasatch Range in Utah and Idaho, and in the headwaters of the Rio Grande in Colorado and New Mexico. In addition, the separate basin of Puget Sound and Willamette Valley in Washington and Oregon is surrounded by ranges of high water yield.

Chiefly because of the water flowing into it from the Sierra Nevada, California's Central Valley is the largest and most productive agricultural area in the region. Far less water drains from the steep eastern slope of that range, but it is still enough to sustain some of the largest cultivated areas in

Nevada, and to provide an important part of the water supply for the city of Los Angeles.

More than two-thirds of Utah's population, industry, and cultivated land are concentrated in a 150-mile strip where they can use the water draining from the Wasatch Range. Even with this use, much of the outflow from those mountains goes to waste in Great Salt Lake, from which water is evaporated at an average rate of 2 to 3 billion gallons per day. At the headwaters of the Rio Grande, the San Luis Valley is another basin amply supplied with water, and the surplus moves downstream to serve the water needs of many of the people of New Mexico and some of Texas.

Several of the isolated mountain ranges within the arid-basin region are high enough to catch heavy precipitation, and to yield moderate to large quantities of water to adjacent valleys. Noteworthy among these are the ranges at the headwaters of the Salt and Gila Rivers in Arizona and New Mexico, the San Gabriel and San Jacinto Mountains in southern California, and the Humboldt and Deep Creek Ranges in Nevada and Utah. The coast ranges of California are much lower but better situated for reciving precipitation, and they also produce considerable stream flow as a result of precipitation throughout the winter.

The largest stream crossing the arid-basin region—the Colorado River—is also the most difficult to harness for use within the region. Here is a river draining several of the highest ranges in Colorado, Wyoming, and Utah, and carrying more water each year than the total inflow to the San Joaquin Valley in California. But the water in San Joaquin Valley serves more than a million acres of cultivated land, whereas the Colorado is practically devoid of good agricultural land along its course. Beginning in the 1890's increasing quantities of water have been diverted from the river into some arid basins. Currently some of the bitterest arguments of the West are generated by competition among the residents of several of the arid basins for rights to the use of water that is still going to waste in the Gulf of California.

The Colorado River is one of the rare exceptions among streams of the region, in that it carries some water that is still available for man's development and use. Most of the perennial streams are fully appropriated for use, and indeed large areas within the region are remote from any perennial streams. The region is a have-not region, not only as to precipitation, but also as to stream flow.

The Ground-Water Reservoirs

The arid-basin region is far ahead of all other regions in ground-water development. Wells in the arid basins yield more than half of all the water produced by wells throughout the Nation. Some of the reasons for this preeminence have already been indicated: Almost every landowner in the region must have more water than his land receives in the form of rain; and surface water, although doing yeoman service for the present population, is too meager to meet any great increase in demand. The chief reason for the importance of ground water in the region, however, is the existence of vast quantities of water in underground storage.

The productive ground-water reservoirs of the arid-basin region are predominantly—in fact, almost exclusively—in the loose sediment underlying the valley areas. All that sediment has been derived from erosion of the highlands, and has been carried to the lowlands by streams, or in rare instances by glaciers. In the valleys some has been deposited with practically no sorting by torrential streams, and some has been sorted rather thoroughly by streams of more regular flow; some has been deposited in lakes, and some has been reworked by wind action. In most valleys these loose materials, known collectively as *valley fill*, have been accumulating for a long period of geologic history, and now form a flat or undulating land surface that contrasts strikingly with the ruggedness of the adjacent mountain ranges.

The valley fill is known to be hundreds of feet deep in many valleys, and in some places its depth is several thousand feet. In most valleys there is practically no information as to its actual thickness, because no wells—or at the most, very few—have been drilled through it and into underlying rocks. In some places, notably in Arizona, wells have gone through more than 500 feet of dry fill before reaching ground water, but in most valleys there are extensive areas where the valley fill is saturated to a level within a few feet of the land surface. Comparison of the depth to the water table and the depth of valley fill penetrated by wells suggests that the great bulk of the valley fill is saturated with water in most valleys.

There are many thousands of irrigation wells in the arid-basin region, and their capacities range from moderately large to prodigious. The large wells generally obtain water from aquifers of gravel and sand which are numerous in most valleys, and especially common near the mouths of the canyons of mountain streams. However, gravel and sand beds generally constitute only a small part of the total valley fill. Many wells can yield only enough water for domestic or stock use; they take water from poorly sorted alluvium, or from thin sand beds, or from porous but poorly permeable surficial material.

The ground-water storage in arid basins is so great that, in the enthusiasm of early stages of development, ground-water supplies were regarded as "unlimited" or "inexhaustible." Now that wells have been pumped for nearly half a century in some basins, there is abundant evidence that the quantity of ground water in storage has been seriously depleted. Indeed, substantial depletion has occurred in some basins after only a few years of pumping. In many valleys it has been found that, although great volumes of water have been stored underground by nature, the yield that can be sustained year after year is small. The upper limit of perennial yield is set by the average annual replenishment to the reservoir; the practical limit is less, and in some places far less, than this quantity.

The ground-water reservoirs of the arid basins are recharged chiefly by seepage from streams flowing from the bordering mountain ranges. The quantity of recharge is

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limited, just as the volume of stream discharge from the canyons is limited, in most of the region. Downward percolation of precipitation in the valley area is also a source of ground water, and in some valleys or parts of valleys it is an important factor in recharge. As a rule, however, the arid basins depend upon the tributary mountain ranges for their ground-water as well as surface-water supplies.

The arid-basin region has a large number of separate and independent ground-water reservoirs, and they are in almost every stage of development, from those that are practically unused and capable of considerable development to those that are capable of very little sustained perennial use and are seriously overdeveloped (fig. 9). Although the overdeveloped reservoirs have received much more public comment, there is a far larger number of basins in which the ground-water reservoirs are not overdrawn, and from which more water could be pumped on a sustained basis than is currently being withdrawn.

Nevertheless, all the arid basins are characterized by a limited water supply—much less than could be used on the arable land in them. And the basins where surface- and ground-water supplies are still adequate, or perhaps more than currently needed, differ from the overdeveloped areas chiefly in the degree of development and use of water. They, too, can reach a critical point at some stage of increased development, because there just isn't enough water to meet demands comparable to those that can be satisfied in regions of abundant rainfall. (See figs. 8, 10, 11, and 12.)

Many travelers crossing the arid basins note the numerous "alkali flats," and take them to be one of the indications of lack of water in a desertlike region. Actually water is likely to be very close to the surface in those areas, and "alkali" is a good indication that water is being wasted from the basin by natural processes. The alkali flats, however, do tie in with the general aridity of the region, for they could not exist in the humid climates of the East. The soluble salts would quickly be dissolved if precipitation were adequate, and would be carried either in streams or ground water to an eventual resting place in the ocean. Thus the

FIGURE 8.—*Natural discharge of ground water in Parowan Valley, Utah. Evaporation from pool formed by a spring, and transpiration by greasewood.*

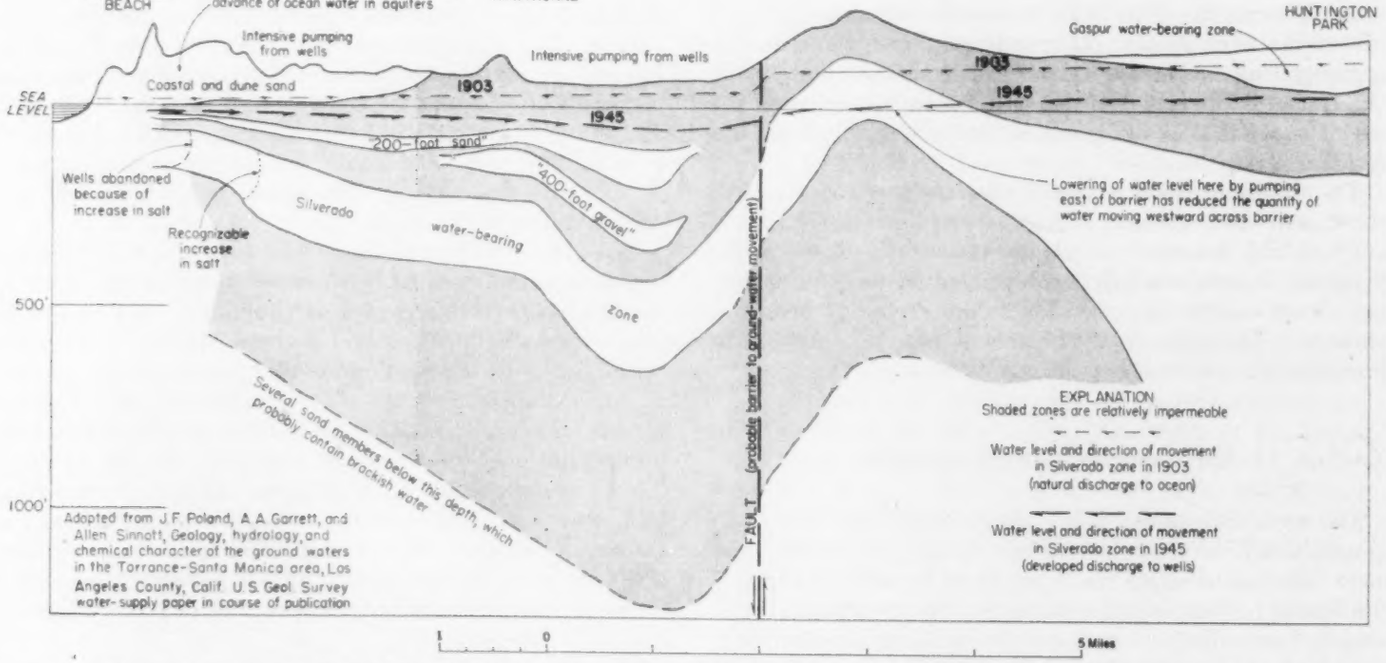
SW.
Newport-Inglewood structural zone
NE.
MANHATTAN BEACH
Recharge here with fresh water may stop advance of ocean water in aquifers
HAWTHORNE
HUNTINGTON PARK
Intensive pumping from wells
Intensive pumping from wells
Gaspur water-bearing zone
SEA LEVEL
Coastal and dune sand
1903
1945
1903
1945
"200-foot sand"
"400-foot gravel"
Wells abandoned because of increase in salt
Recognizable increase in salt
Silverado
water-bearing
zone
Lowering of water level here by pumping east of barrier has reduced the quantity of water moving westward across barrier
500'
1000'
Several sand members below this depth, which probably contain brackish water
FAULT (probable barrier to ground-water movement)
EXPLANATION
Shaded zones are relatively impermeable
Water level and direction of movement in Silverado zone in 1903 (natural discharge to ocean)
Water level and direction of movement in Silverado zone in 1945 (developed discharge to wells)
Adapted from J. F. Poland, A. A. Garrett, and Allen Sinnott, Geology, hydrology, and chemical character of the ground waters in the Torrance-Santa Monica area, Los Angeles County, Calif. U.S. Geol. Survey water-supply paper in course of publication
1
0
5 Miles

FIGURE 9.—*Section of Los Angeles, Coastal Plain, Calif. Intensive pumping, by lowering water levels, has reduced the rate of ground-water movement across a natural barrier and caused encroachment of salt water.*

FIGURE 10.—*A critical area of the Los Angeles Coastal Plain, Manhattan Beach, Calif. Four municipal wells at reservoir (R) and another farther north (W) have been abandoned because of intrusion of salt water from the Pacific Ocean, which is a mile to the west (beyond left edge of photo). Wells in the right half of area still yield good water.*

oceans perform a service for most of the continental masses of the earth, by accepting the soluble salts that are carried to them in streams and ground water. The surface and ground waters in the arid basins carry mineral matter in solution, too; but, as most of that water cannot get to an ocean, the region itself must perform the function normally undertaken by the ocean. In closed basins, all water from precipitation returns eventually to the atmosphere, and all dissolved matter must be left behind, in the basin. Accumulation of soluble salts at the point of evaporation is inevitable. The alkali flats and salt lakes are areas of such accumulation. Great Salt Lake is one of them, and on a grand scale. The entire arid-basin region has this problem of salt accumulation in lakes or streams, or in soils or ground water.

One of the most productive parts of the arid-basin region is the Gila River Basin in Arizona. This basin has already encountered many of the problems that may ultimately plague other arid basins during their development of water resources: overdevelopment of ground water, complicated relations between ground water and surface water, large natural waste, and increasing salinity of water. The basin includes about half the area of Arizona and more than 90 percent of its population, industry, and irrigated land. There are several individual ground-water reservoirs, from which more than 3,000,000 acre-feet is pumped annually; and in several areas water levels have declined more than 30 feet in the past two decades. In 1948, more than three-fourths of all water used in the basin was pumped from wells. Hydrologic data are not complete enough to warrant estimates of the average annual replenishment, or even of the amount of pumped water that returns to the ground-water reservoir.

In some localities there has been a tremendous increase in pumpage in the past decade. Deer Valley, north of Glendale, Ariz., is typical. Between 1940 and 1948, 80 large wells were drilled to irrigate more than 21,000 acres, and annual pumpage increased from 600 to 88,000 acre-feet. In the 8 years water levels declined an average of more than 70 feet throughout the irrigated area—more than 20 feet in a single year (1948). The average pumping lift in 1948 was about 270 feet (Bluhm and Wolcott, 1949).

Evapotranspiration losses are large in the hot deserts of the Gila River Basin. Probably more than 500,000 acre-feet is discharged each year from ground-water reservoirs by nonbeneficial vegetation, mostly salt cedar, along the Gila River below Coolidge Reservoir, the Salt River below Phoenix, the Verde below Bartlett Dam, and the San Pedro River (Turner, 1951). In addition, there are large losses by evaporation from surface reservoirs on the Verde, Salt, and Gila Rivers, which might be reduced if the water could be stored underground instead, beyond the reach of the hot Arizona sun.

FIGURE 11.—*Contour trenches near Centerville, Utah. These are designed to prevent erosion of the steep west slope of the Wasatch Range. The pond is filled with surplus water from Centerville Creek to recharge the aquifers in the Centerville area. Conservation program initiated by United States Forest Service.*

FIGURE 12.—*Canals and spreading areas for artificial ground-water recharge along the Rio Hondo near Whittier, Calif. Part of the coordinated program of flood control and water conservation by Corps of Engineers, United States Army, and Los Angeles County Flood Control District.*

The outflow from the Gila Basin has been reduced to a trickle by the greatly increased utilization of water within the basin. In recent years there has been no surface outflow except for a few days following heavy storms in the lower part of the basin, and the underflow down the Gila channel is considered to be only a few hundred acre-feet a year. The inevitable result of this cessation of outflow has been an increased rate of accumulation of salts in the lower part of the basin—an accumulation that is already detrimental in ground waters near the Gila River channel for more than 150 miles from the mouth (Babcock and others, 1947). The use and reuse of water for irrigation has contributed some of this salt to the lower valley, by dissolving soluble materials in the soil zone. Part of the salt originates in saline springs within the basin, or from rocks such as the "salt banks" along the Salt River near Chrysotile. For instance, the Clifton Springs contribute about 4 acre-feet of water and 60 tons of salt daily to the San Francisco River. Diluted by the Gila River, that water becomes entirely suitable for irrigation, and the salt spring thus gives a small advantage in quantity of water available in Safford Valley. As the

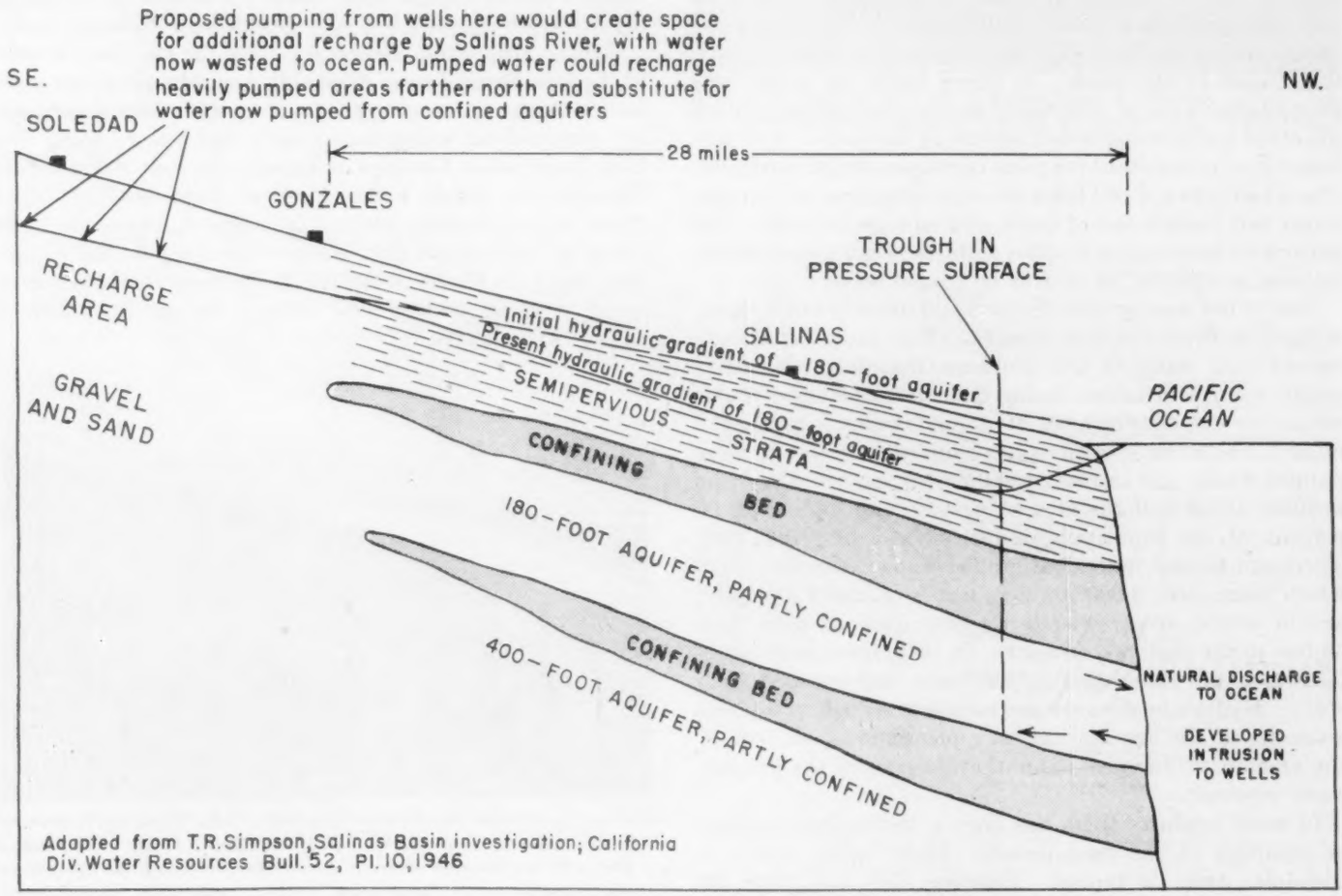
Proposed pumping from wells here would create space for additional recharge by Salinas River, with water now wasted to ocean. Pumped water could recharge heavily pumped areas farther north and substitute for water now pumped from confined aquifers
SE.
NW.
SOLEDAD
28 miles
GONZALES
TROUGH IN PRESSURE SURFACE
RECHARGE AREA
SALINAS
Initial hydraulic gradient of 180-foot aquifer
Present hydraulic gradient of 180-foot aquifer
PACIFIC OCEAN
GRAVEL AND SAND
SEMIPERVIOUS STRATA
CONFINING BED
180-FOOT AQUIFER, PARTLY CONFINED
CONFINING BED
400-FOOT AQUIFER, PARTLY CONFINED
NATURAL DISCHARGE TO OCEAN
DEVELOPED INTRUSION TO WELLS
Adapted from T.R. Simpson, Salinas Basin investigation; California Div. Water Resources Bull. 52, Pl. 10, 1946

FIGURE 13.—*Longitudinal section of Lower Salinas Valley, Calif.*

salt reaches the lower part of the basin, though, it is a great detriment; each day's addition of 60 tons is enough to make 40 acre-feet of fresh water unusable for irrigation.

The central Arizona project proposes the importation of 1,200,000 acre-feet annually from the Colorado River, to offset the current overdraft on the ground-water reservoirs and to permit the flushing of excess salt from the basin. Until such a quantity of water is available, the Gila Basin faces prospects of increasing difficulties, some of which may be alleviated, however, by salvaging water now wasted by transpiration and evaporation, and by taking measures to reduce the salt inflow to the basin's water supply. Even with the importation of large quantities of water from the Colorado River, efficient use of the water resources would require expert water management, based upon an adequate knowledge of the hydrology of the region. The huge facilities for underground storage constitute the only means of storing water for use without losing significant quantities by evaporation, and they can play an important part in the ultimate development of the basin.

In some arid basins where pumping currently is at a greater rate than the natural replenishment to the ground-water reservoir, effective utilization of underground storage facilities would enable the water users to harvest more water perennially than is now being used. The Salinas Valley in central California is an example, as is brought out in a report of investigations by the Division of Water Resources of the State of California (Simpson, 1946). The annual pumpage from wells in this valley is of the order of 370,000 acre-feet, which is about 30,000 acre-feet more than the average annual replenishment. But more than 500,000 acre-feet flow unused from the valley into the Pacific Ocean in an average year, of which about 90 percent is the winter flow of the Salinas River.

There are significant differences in opportunities for natural replenishment in different parts of the Salinas Valley (fig. 13). Pumpage from the upper half of the valley has been of the order of 210,000 acre-feet a year, but there is no overdraft; indeed, there is more than 100,000 acre-feet of water in storage within 60 feet of the surface, on which draft has never been made. This is the part of the ground-water reservoir most readily recharged by the Salinas River and its tributaries. In some places in this upper valley, however, there has been a gradual accumulation of soluble salts in the ground water, because of irrigation and inadequate ground-water outflow, aggravated by chemical fertilizers. At Soledad, for instance, the dissolved solids increased from 350 parts per million in 1932 to 640 in 1945, and to 900 parts per million in 1949.

Along the lower east side of the valley, the pumpage of 35,000 acre-feet is about 7,000 acre-feet greater than replenishment, and the water table has been receding at an average rate of 4 inches a year. In the "pressure area" comprising the lowest part of the valley, water is confined in aquifers under artesian pressure. The pumping draft of 120,000 acre-feet in the pressure area must be replenished by lateral movement from adjacent areas; that replenishment is less than the pumping draft, and in recent years it is estimated that during the pumping season about 6,000 acre-feet of saline water has intruded into the "180 foot" aquifer from Monterey Bay.

If 5 percent of the present surface outflow to the ocean could be salvaged and put to beneficial use, present overdrafts in the east-side and pressure areas could be eliminated; and if 15 percent of that outflow were salvaged water would be available for 50,000 acres of irrigable land in the valley that is not now irrigated. According to the comprehensive plan of development recommended by the State engineer, water would be pumped from the river gravels above the pressure area and diverted through canals to recharge the east-side area, where there are unsaturated gravels capable of storing about 200,000 acre-feet of water. The gravels above the pressure area would be replenished from winter stream flow in normal years, and this salvage would be of

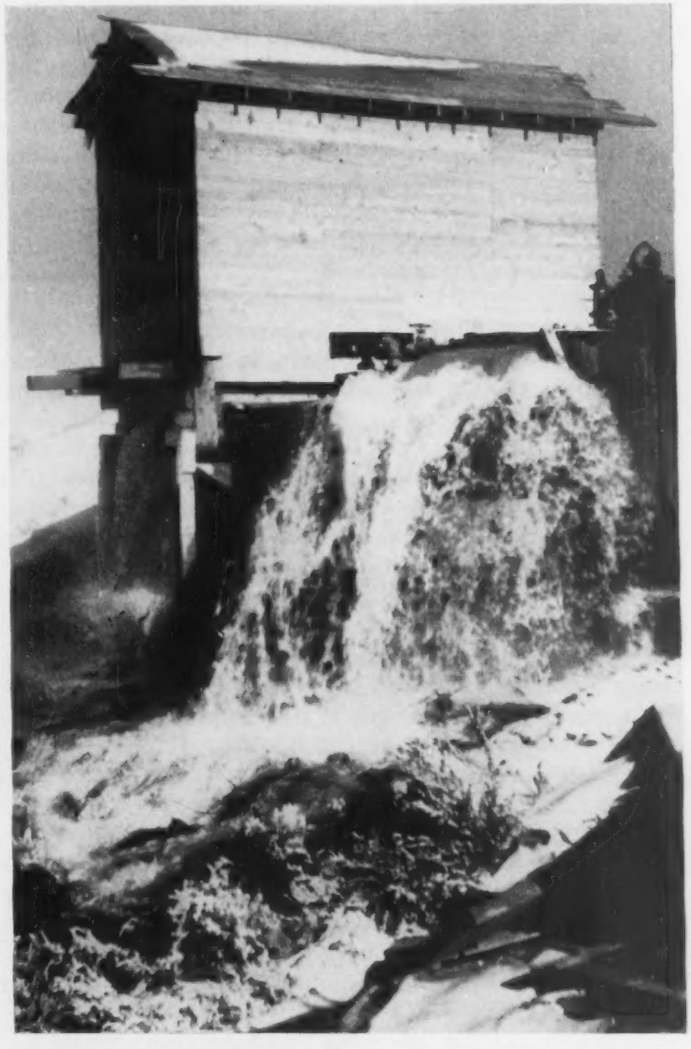

FIGURE 14.—*Mine drainage at Eureka, Nev. The Eureka Mining Co., Ltd., pumps 7,500 gallons per minute with a lift of 1,800 feet, in order to continue mining operations. Overabundance of water is a rare affliction in the arid-basin region.* (*Photo by O. J. Loeltz, U. S. Geological Survey.*)

material advantage in providing ground-water storage to tide over dry years. Salt-water encroachment in the lower pressure area could also be reduced by increasing the irrigation efficiency there, so as to eliminate all pumping in excess of beneficial requirement.

Little is known concerning the ground-water reservoirs of the mountain ranges and other uplands in the arid-basin region. The mantle rock in these areas is generally thin, and the underlying consolidated rocks probably are relatively impermeable for the most part. The water released from these rocks is small, as shown by the low base flow of the few perennial streams. Nevertheless, the rocks of the mountains doubtless hold large volumes of water in storage. Some mining properties have ample proof of this, because they must pump huge quantities of water from their workings in order to continue operations (fig. 14).

Columbia Lava Plateau

Summary

EXTENSIVE HIGH, rather dry dissected plateaus underlain by lava rocks in eastern Washington and Oregon and southern Idaho. Included are a few low basins partly filled with alluvium.

The region is traversed by the Columbia River and its tributaries, particularly the Snake River, flowing generally in deeply incised valleys. The water is derived mainly from the mountains. It is extensively used for irrigation where there are sizable areas of valley floor or intermediate benches. The lava contains highly permeable zones and readily absorbs water from precipitation and from irrigated fields. The underground water forms a tremendous body that helps to sustain stream flow and feeds some of the world's largest springs.

There is need for additional water for irrigation and for power production, and these needs conflict to some extent. There is considerable waterlogging of some low tracts as a result of a rise of the water table caused by irrigation with surface water on higher land.

There is great promise for development of ground water from some of the productive lava-rock aquifers, and for use of the underground reservoirs to store floodwater and thus further to even out irregularities in stream flow and to reduce the need for surface reservoirs.

This is one of the most imperfectly known ground-water regions in the country. Its promise can never be realized until both the general principles of the hydrology of lava rocks and the details of occurrence of water in each part of the region are better understood. Especially needed is information on the relation of ground-water movement to stream flow under present conditions, as a guide to future utilization of the underground reservoirs to produce the maximum useful water supply and to improve stream-flow regularity.

The Columbia Lava Plateau region includes most of eastern Oregon, eastern Washington, southern Idaho, and small parts of Nevada and Utah (fig. 15). It corresponds to Meinzer's Columbia Plateau lava ground-water province. The region is generally lower than the western mountain ranges (the Cascades and Rocky Mountains) which border it on the west, north, and east, but it is nevertheless elevated considerably above sea level. Altitudes are generally above 1,000 feet and in a few places reach 10,000 feet.

Most of the region is within the drainage basin of the Columbia River and especially its tributary, the Snake. In southern Oregon and adjacent parts of California and Nevada, the volcanic rocks extend into the arid-basin region. In that area there is an overlapping of the ground-water reservoirs that dominate the two regions, and water may be obtained both from the valley fill of closed basins and from the volcanic rocks.

A major feature in the geologic history of the Columbia Plateau region has been the vast outpouring of lavas. Some of the most recent and most conspicuous effects of this volcanic activity are in the craters of the Moon National Monument in Idaho, but the entire region has a long history of volcanic action and is the outstanding volcanic terrane of the country. Lava flows have obliterated ancient drainage patterns and formed extensive plains.

The region, however, is by no means flat. In many places the streams have cut into the lava plains and formed deep canyons, some of which (like Grand Coulee) are no longer occupied by the streams that formed them. Numerous cones and ridges marking volcanic vents project above the level of the broad plains. And the older lavas have been subjected to mountain-making stresses; now there are numerous anticlinal mountain ranges and prominent fault scarps in the region. The Wallowa Range, in northeastern Oregon, with some peaks about 10,000 feet above sea level, is one of the highest areas in the region.

The climate of the Columbia Plateau region ranges from arid to humid. The average annual precipitation is less than 10 inches in extensive areas of the Snake River plain in Idaho, and in areas east of the Cascades in Oregon and Washington. In most of the region the annual precipitation ranges from 10 to 20 inches. In the Wallowa Mountains it may exceed 30 inches.

The Columbia Plateau region is well populated, by western standards. Most of the people of Idaho live on the Snake River Plain. Eastern Washington likewise has several hundred thousand people, although the region is less densely populated than the Puget Sound region in the western part of that State. Relatively few people live in the plateau region of Oregon, however.

Generally the inhabited areas are the lower and more arid parts of the region. The rainfall in many of these areas is sufficient for dry farming, and wheat is an important crop in those areas. Most of the agricultural crops, however,

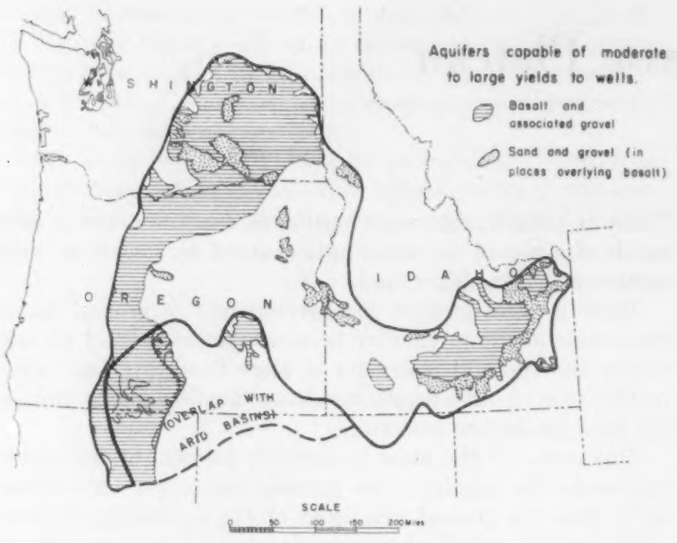

FIGURE 15.—*Columbia Lava Plateau: large and excellent storage in reservoirs of volcanic materials.*

are irrigated, and the chief sources of water for irrigation are the streams that drain the high ranges bordering the plateau region. Probably no major stream in the country is more intensively used for irrigation and power than the Snake River in Idaho. The use of ground water for irrigation and industry is increasing, and extensive development has been made in some areas, notably in the vicinity of Spokane and in south-central Idaho.

Natural Facilities for Regulation of Stream Flow

Great changes are wrought in any drainage system inundated by lava flows. In the Columbia Plateau region the lavas are of the basaltic type and were fluid when erupted; in rugged areas they invariably follow stream channels. Throughout the region the valleys of streams coming from the Cascades or Rocky Mountains have been obliterated, and broad lava plains have been formed, later to be disrupted in many places by folding and faulting.

The basalt lavas are in an excellent position to receive the water that flows into the region from the bordering mountains, for they lie in or athwart the lower parts of the stream valleys. In some places the lava is permeable enough to absorb much of the stream flow, as is the case with the Big Lost River and Little Lost River in Idaho. Some streams have formed lakes where they flow out over less permeable volcanic material, and many have established new channels across the volcanic terrane.

The lavas of the region have sufficient volume and porosity to hold vast quantities of water. The Snake River Plain provides a noteworthy example. For 200 miles along its north side all the rivers descending from the mountains sink into the porous lava. The volume of water is so great that the basalts are saturated for a considerable thickness above the underlying impermeable rock, and the water table slopes gently southwestward. Near the west end of the central lava plain, great quantities of water are discharged by springs from the ancient lava-filled canyons of the Snake River. The inflow to this ground-water reservoir fluctuates considerably from season to season, and is greatest in the spring when streams are swollen with water from melting snow. The outflow through springs is far more constant, both seasonally and annually. Thus the ground-water reservoir serves as a natural regulator of flow in the Snake River, receiving recharge especially when tributary streams are in flood, and releasing the water at relatively constant rates.

The Metolius River in central Oregon is an outstanding example of a stream whose discharge is well regulated by a ground-water reservoir. Piper (1948, p. 516) describes the characteristics of the flow of that river near Grandview, Oreg., as follows:

> . . . drainage area, approximately 325 square miles, there is neither diversion from, nor regulation of the river above the gaging station. Flow characteristics are as follows: Mean yearly runoff, 1,023,900 acre-feet, or 58.50 inches depth on the drainage area; equivalent uniform flow, 1,413 cubic feet per second; recorded extremes 5,780 and 1,080 cubic feet per second, or 410 and 76 percent of the mean. It is noteworthy that drainage area is only 3 percent, but mean runoff is 24 percent of that of the Deschutes River, to which this stream is one of the principal tributaries from the west. In terms of depth on the drainage area, the mean yearly runoff from the basin of the Metolius River is 7.8 times that from all the basin of the Deschutes; probably it exceeds mean yearly precipitation on the drainage area. Here, runoff is uncommonly steady indeed; minimum flow, essentially all of which is perennial ground-water runoff, proportionately is 1.30 times that in the Deschutes and is several thousand times that in the John Day.

In contrast, the John Day River at McDonald Ferry has a drainage basin of 7,580 square miles, also in central Oregon, as follows:

> The gaging station is below numerous small diversions for irrigation, but doubtless is below essentially all the return flow from that irrigation; mean yearly runoff (for the 25 years, October 1, 1920–September 30, 1945), 1,274,200 acre-feet, or 3.15 inches depth on the drainage area; equivalent uniform flow, 1,758 cubic feet per second; recorded extremes of flow, 24,900 and 4 cubic feet per second; that is, 1,420 and 0.002 percent of the 25-year mean. As these extremes indicate, the stream is excessively "flashy" (even though the measured minimum flow doubtless is moderately less than the natural minimum, owing to depletion by diversions), and perennial ground-water runoff is insignificant in amount.

Ground-Water Reservoirs in Volcanic Materials

The rocks cropping out in the Columbia Plateau region consist almost entirely of the products of volcanic eruptions, sedimentary rocks derived from those volcanic materials, and dikes, sills, or other intrusive rocks that are related to the volcanic activity. This volcanic sequence rests upon impermeable rocks, so deeply buried in most of the region that they have not been uncovered in the deepest canyons, and have been encountered in very few wells.

In some places, notably near the borders of the region, the

volcanic materials are less than a hundred feet thick, and may be the product of a single eruption. Generally they are hundreds or even thousands of feet in thickness. These great thicknesses are produced by many individual lava flows, some of which are readily discriminated by the characteristic *interflow* zones that separate them. Commonly the individual lava flows are 20 to 500 feet thick.

The rocks have a very wide range in water-bearing properties. In the western part of the region, the interflow zones are generally the most permeable in the sequence, and are therefore the ones to be sought by wells. Farther east in Idaho, the pore space is provided chiefly by fractures. In many places the lava is so broken up that it is practically a rubble, and gas bubbles, vegetation molds, lava tubes, or even small caverns may add to the pore space. Very permeable gravel and sand beds also occur in the volcanic sequence. Some of the most productive wells in the Nation obtain water from the permeable lava and associated gravels of the Columbia Plateau region. However, the volcanic series is so permeable and the relief of the region so great that in many places the water table is several hundred feet below the land surface.

The massive lava flows are generally impermeable, and this is true also of most of the intrusive rocks, such as dikes or sills or plugs, in the region. Some of the sediments interbedded with the basalts, notably the clay beds, are also impermeable. These rocks are unsatisfactory producers of water to wells. They are also the great hindrances to vertical movement of water, and thus may prevent recharge to underlying permeable zones.

Impermeable zones produce many perched ground-water reservoirs, evident for instance in the Palouse-type soils in many places, and in the *layered* character of seeps and springs along canyon walls and hillsides. Perched ground-water reservoirs are also indicated by drilling experiences in many wells: water encountered at shallow depth drains through the well into deeper unsaturated materials as the drilling progresses.

Where impermeable beds lie above saturated water-bearing materials, they may confine the water under artesian pressure that may be sufficient to produce flowing wells. The noteworthy variations in permeability of volcanic materials near Twin Falls, Idaho, have been mentioned.

In parts of the Snake River Plain, the volume of water stored in and discharged from the ground-water reservoir has been increased by man's use of surface water for irrigation. The famous Thousand Springs and other large springs along the canyon of the Snake between Milner and King Hill now discharge considerably more water than they did 50 years ago. In 1902, before irrigation, the total discharge of springs in this reach was about 3,800 second-feet. The average inflow to the Snake River, between Milner and King Hill, derived chiefly from these springs, increased to 4,900 second-feet by 1910, ranged from 6,800 to 7,600 second-feet between 1920 and 1940, and has exceeded 8,000 second-feet since 1942. This increase results largely from return flow of water used for irrigation north of the river (fig. 16).

It has been estimated that under existing conditions of replenishment from irrigated lands and from natural sources, the ground-water reservoir under the Snake River Plain above King Hill yields 3,600,000 acre-feet annually by spring discharge, and the reservoir below King Hill might yield an additional 1,000,000 acre-feet annually. The Minidoka project of the Department of the Interior proposes (Nace,

FIGURE 16.—*Thousand Springs, Idaho. Along the canyon of the Snake River, before power development*

1948) to develop, within 11 years, a total of 241,000 acre-feet per year of this water, and to observe closely the effect of this development on the ground-water reservoir. The project involves irrigation of about 66,000 acres by pumping from 150 or more wells, each with a pumping capacity of 3 to 10 cubic feet per second.

Ground-Water Reservoirs in Alluvium

Unconsolidated beds of gravel and sand are important sources of water in many parts of the Columbia Plateau region. Glacial outwash deposits in the vicinity of Spokane are exceedingly permeable, and wells dug by the city yield as much as 57 million gallons a day each with a drawdown of less than six feet. In the vicinity of Walla Walla many irrigation wells are drilled in valley fill, and those wells are comparable in many respects to the ones in the closed basins of the arid Southwest. In several other places wells have been drilled in valley fill and are pumped for irrigation.

In many places the unconsolidated materials above the basalt have been irrigated from streams, with the result that some of those materials have been saturated, and irrigated lands have become waterlogged. In extensive areas in Idaho, including the Boise, Weiser, and Payette Valleys, and minor parts of the Mountain Home area, the water table has risen until the land is no longer suitable for cultivation, and serious drainage problems have developed.

Colorado Plateau

Summary

EXTENSIVE dissected arid and semiarid plateaus underlain by stratified sedimentary rocks in the "Four State" region of Utah, Arizona, New Mexico, and Colorado, and also in Wyoming.

This is a large region whose water requirement is small in comparison to that of more heavily populated regions. Yet its need for water is greater than its ability to produce water. Only the highest plateaus catch enough precipitation to serve as sources of substantial amounts of water for adjacent areas. On the whole, the plateaus yield only small amounts of runoff with disproportionately high contents of dissolved and suspended solids. As aquifers the rocks underlying the plateaus are generally poor. They are not highly permeable, and all but those exposed on the plateau surfaces are poorly situated to receive water even if precipitation were more abundant.

Because of generally deficient rain and snowfall and of scarcity of productive aquifers and great depth to some beneath the plateau surfaces, there is a lack of adequate water supplies even to support grazing, to say nothing of irrigation agriculture.

Careful hydrologic study and prospecting for water have paid dividends in many areas of chronic shortage of water for domestic and stock use. It is evident that considerably more water can be obtained from the ground than has been developed so far, and there is good reason to hope that location of additional wells will permit more profitable and better-distributed grazing in hitherto inaccessible areas, as well as more adequate domestic supplies. The possibilities of irrigation agriculture are small.

This vast region has hardly been touched even by reconnaissance methods of ground-water study. The few studies that have been made show that water supplies can be developed in most places only through careful study of the different rock strata in order to determine which are present within feasible depth and which yield good and which yield poor water. Detailed stratigraphic study of the whole region, therefore, can be expected to lead to a much higher percentage of successful well locations.

In the Colorado Plateau, as elsewhere in the West, there is need for study of induced precipitation, to determine the extent to which precipitation can be increased in dry areas, and the effects, good or bad, on other areas.

The Colorado Plateaus ground-water region lies west of the Rocky Mountains and includes parts of the States of Wyoming, Colorado, Utah, New Mexico, and Arizona (fig. 17). It includes two physiographic provinces as delimited by Fenneman (1930): to the north, the Wyoming Basin, which is almost completely enclosed by ranges of the Rocky Mountain provinces; and the Colorado Plateaus, which include individual plateaus ranging from less than 3,000 to more than 12,000 feet above sea level. The region is bounded on the north and east by the western mountain range ground-water region, and on the south and west by the arid-basin region. It includes most of Meinzer's Montana-Arizona ground-water province, but it does not extend into Montana.

Most of the Colorado Plateau region is within the drainage basin of the Colorado River. The larger tributaries of the Colorado—the Green, upper Colorado, Gunnison, Dolores, and San Juan—head in the western mountain ranges, but their drainage areas are mostly within the plateau region. Many smaller tributaries—the San Rafael, Dirty Devil, and Little Colorado for example—drain the plateau region exclusively. Small parts of the Colorado Plateau region are drained by tributaries of the Yellowstone, the Platte, the Rio Grande, and streams flowing to the Great Basin.

A plateau is defined as an elevated tract of land, or a tableland. This region obviously deserves the title, for no part of it is less than 1,000 feet above sea level, and most of it is more than a mile high. The height of the region is most formidable and impressive when viewed from the Arid Basin region, for the plateau surfaces commonly rise well above the crests of the isolated ranges of the arid basin region. Where the region is bordered by the western mountain range region, however (as in Wyoming and Colorado), it becomes the lowland area by contrast with the still higher ranges.

In detail the plateau region is a large number of "intermediate steps" at various elevations, some as much as 12,000 feet above sea level, others far lower. Some of these individual plateaus are relatively flat, but many have been severely dissected by erosion. The larger streams have cut canyons hundreds or even thousands of feet deep into these plateau surfaces. The Grand Canyon of the Colorado stands out as the deepest of those canyons but there are hundreds of others throughout the region. Because of this dissection, most of the broad, level or gently sloping areas of the region are high, and most of the steep slopes are downward from those tablelands into canyon bottoms. The topography is thus the reverse of that in the surrounding western moun-

tain range and arid basin regions, where the flatter lands are characteristically lowlands, from which the ranges project upward.

Most of the rocks of the plateau region are sedimentary rocks, and most of those sediments are flat lying. The differences in elevation of the individual plateaus are generally due to faulting. However, in some places those sediments now form broad arches and troughs, and locally they are sharply folded as in the Waterpocket Fold, or flexed as in the Comb Monocline (both in southeastern Utah).

The region includes several prominent mountains that project sharply above the plateau surfaces, most of them piles of igneous rock. Among these are the LaSal Mountains, Henry Mountains, Abajo Mountains, and Navajo Mountain in eastern Utah, and the San Francisco Peaks southeast of the Grand Canyon in Arizona. These mountains occupy a very small part of the total area of the region.

The climate of the plateau region is arid to semiarid. Topography is an important factor controlling precipitation in the plateau region with its isolated mountain ranges, high plateaus, intermediate plateaus, low plateaus, and canyons. The precipitation is generally intermediate between that in tha arid basins and that in the western ranges. No part of the plateau region is quite so arid as some of the desert basins of the Southwest; on the other hand, very few places receive precipitation equivalent to that in most of the Rockies.

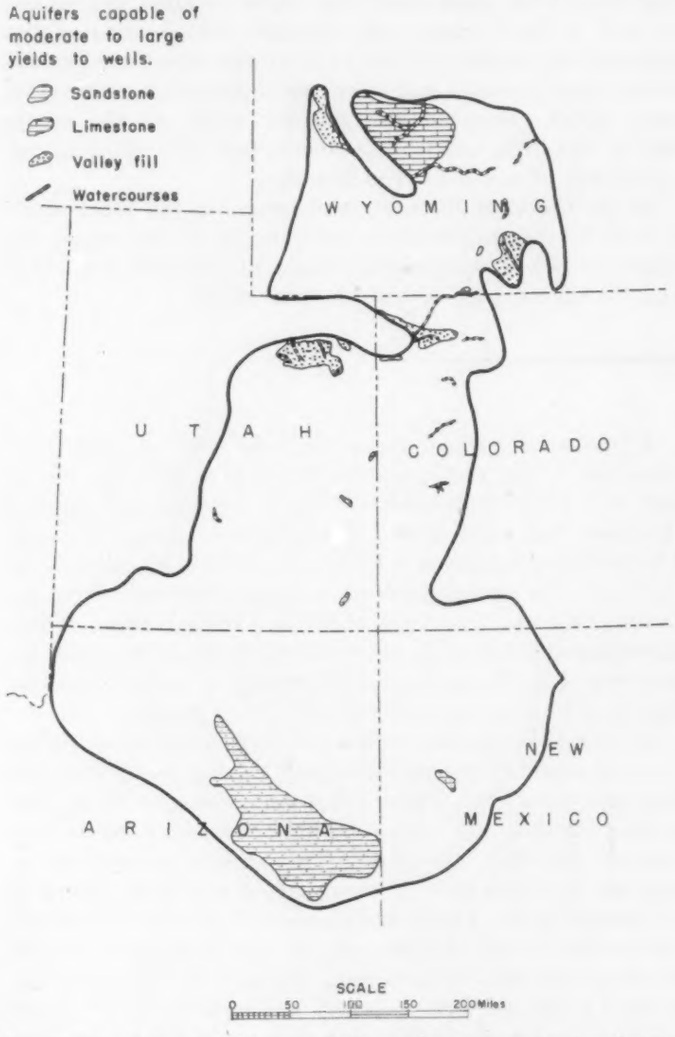
Aquifers capable of moderate to large yields to wells.
Sandstone
Limestone
Valley fill
Watercourses
W Y O M I N G
U T A H
C O L O R A D O
N E W
M E X I C O
A R I Z O N A
SCALE
0 50 100 150 200 Miles

FIGURE 17.—*Colorado Plateaus: chiefly sandstone reservoirs breached by canyons and faults.*

The Colorado Plateau region supports a very small proportion of the Nation's population. It includes the least populous areas of the States of Utah, Colorado, Arizona, and New Mexico, and the only towns having a population of more than 10,000 are Rock Springs in Wyoming and Grand Junction in Colorado. The region as a whole has a density of population far lower than that of the arid basin region, and lower even than the sparsely inhabited western mountain ranges region. Large areas are entirely uninhabited, for the small population is concentrated in the relatively few and small areas of fertile alluvial soil, and in mining settlements. On many of the plateaus the growing season is too short for cultivated crops, and they are therefore suitable only for grazing.

The Poverty of Natural Storage Facilities

It is characteristic of the plateau country that the areas where precipitation would come nearest to meeting the needs of crops are too high and cold for raising those crops. As in the arid basins, irrigation is necessary in most areas where crops can be cultivated, although there are a few notable exceptions, as in the pinto-bean country of southwestern Colorado and southeastern Utah.

Most of the agricultural communities of the plateau region are dependent upon the western mountain ranges for irrigation water. Many are near the bases of those ranges but some, like Grand Junction, Colo., and Greenriver, Utah, are along principal streams at some distance from the mountains. Most of the water of these streams is accumulated throughout the winter as snow on the mountains, and runs off during the spring and summer. As a result, irrigation supplies during the first months of the growing season are notably greater than those later in the season, when most of the runoff comes from ground-water reservoirs. Reservoirs have been constructed on several streams to increase the water supplies available in late July and August.

Although the western mountain ranges discharge much water into the Colorado Plateau region, the opportunities to use that water are severely limited. Downstream from Grand Junction on the Colorado and from Greenriver (Utah) on the Green, the water flows in canyons too deep to be available at reasonable cost to the upland areas, and too narrow to provide any sizable areas of agricultural land near river level. By far the greater part of the plateau region is remote (either vertically or horizontally or both) from the water that originates in the western mountain range region,

and is dependent upon water supplies derived from precipitation within the plateau region

Precipitation within the plateau region is the source of water for many communities and small irrigated areas. Towns such as LaSal, Blanding, and Monticello in Utah are near the bases of isolated mountains that intercept enough precipitation to give rise to perennial streams. Some of the plateaus are the sources of perennial streams: the Aquarius Plateau received its name from the water-bearer of Greek mythology because of the numerous streams flowing from it. The Colorado Plateau region is the principal source of water for several of the arid basins along its margins in Utah and Arizona.

The plateaus that give rise to perennial streams are generally the higher ones of the region. Commonly they are more than 8,000 feet in altitude and many are higher than 10,000 feet. On most of them there is snow accumulation and storage for a part of each year, followed by melting that produces an annual freshet in streams. The plateaus are generally lower than the high Rockies and their snow storage is less satisfactory for irrigation, because the quantity is usually smaller and the period of melting earlier. The snow cover on some plateaus may disappear by February or March. In the rest of the year the discharge of streams consists of occasional torrents from intense rainstorms, and a base flow that comes from ground-water reservoirs. Most plateau streams have an extremely small base flow, even though their drainage area may be several hundred square miles.

In many of the lower drainage areas of the Colorado Plateau region there is little or no accumulation of snow, and therefore no spring freshet. Streams draining areas of several hundred square miles may flow only as a result of intense storms, or they may have a perennial trickle from springs and seeps.

The Colorado River is notorious for the tremendous quantities of sediment that are moved by it each year. Very little of that sediment comes from the headwater areas of the Rockies which produce most of the annual runoff. The great bulk of the sediment load is picked up in the plateau region, and much of it in the storm flow of minor tributaries following intense storms. Some tributaries contribute very little to the total annual runoff of the river, but make that contribution all in a day or two, as a veritable river of mud.

The high storm runoff and low base stream flow are both indications that the ground-water reservoirs of the region are capable of doing only a mediocre job in regulating the flow of streams draining the region.

The Ground-Water Reservoirs

The ground-water reservoirs of the Colorado Plateau region are mostly in sandstone (figs. 18 and 19), (pl. 6). Few wells now obtain water from limestone, but it is likely that some limestones have good possibilities for development. In relatively few and small areas ground water occurs in gravel and sand of alluvial origin. Little is known of the ground-water conditions in the several isolated mountains that project above the plateau, but in any case their area is only a very small part of the region. In a small area near Loa, Utah, basalt is the source of water for several large flowing wells, and has characteristics similar to the basalts of the Columbia lava plateau region.

FIGURE 18.—*Well at Mesa Verde National Park, Colo. Until July 1950 the principal source of water at Mesa Verde National Park was a well 4,192 feet deep, which obtained water from sandstone. The water had to be lifted more than 1,300 feet by the oil-field pumping equipment. It is warm (110°–120°F.) and highly mineralized, but usable.*

Sandstone is the most conspicuous rock type of the Colorado Plateau region. In the Grand Canyon it forms the white band about 300 feet thick near the canyon rim. Sandstone of similar age but of markedly different color forms the monuments of Monument Valley in northeastern Arizona. The sandstone of Zion National Park is of another age, when most of the plateau region must have been quite like the Sahara, and when wind-blown sand accumulated to depths exceeding 1,000 feet in places. A sandstone of still another age is seen at Mesa Verde National Park. Sand loosened from all these rocks is the surficial material in many parts of the plateau, and auto travel is hazardous in places because of it. No other large region in the Nation contains such a high proportion of sandstone.

Sandstones are the only known sources of ground water in many areas of the plateau region, and since the sandstones

are so extensive they are the principal aquifers of the region. They are tapped by flowing wells in the Little Colorado River Basin in Arizona, and in the San Juan River Basin near Hovenweep National Monument and near Bluff, Utah; some of these wells yield as much as 500 gallons per minute. For the most part, though, the wells in sandstone yield less than five gallons per minute. Such wells, drilled chiefly for domestic and stock use, are widely but sparsely distributed over much of the plateau region. Small flowing wells at Grand Junction, Colo., and community wells on the Navajo-Hopi Indian Reservation are typical. Water is confined under artesian pressure in parts of many aquifers, not confined in many other places. Perched ground-water reservoirs are also believed to be common. In some parts of the plateau area where no wells have yet been drilled, geologic structures appear to be favorable for the occurrence of water in deep sandstones and under high artesian pressure. In such places there is a possibility of wells with yields comparable to the wells drilled into the Dakota sandstone. (See p. 114.)

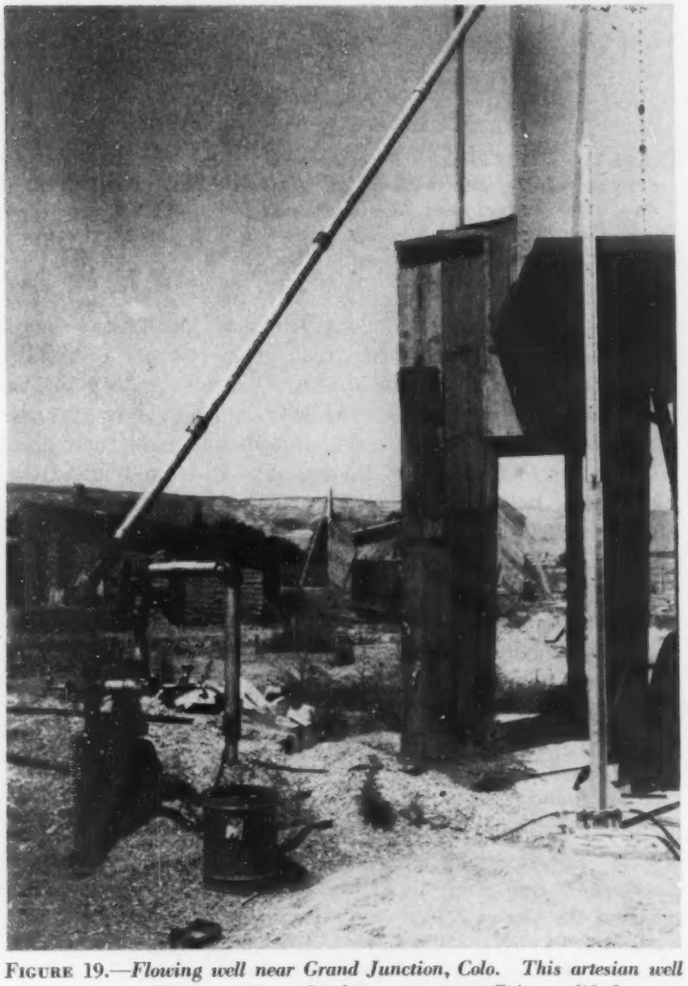

FIGURE 19.—*Flowing well near Grand Junction, Colo. This artesian well flows only 7 gallons per minute, but has a pressure sufficient to lift the water 90 feet above the land surface. The well is 870 feet deep and obtains water from sandstone.*

In many parts of the region wells must go through several hundred feet of unsaturated material before reaching ground water. This is particularly true near the deeper canyons and the major fault scarps, where ground water has been drained from the adjacent rock materials. Along the walls of the canyons of the Colorado and its principal tributaries there are numerous evidences of seepage of water from beds of sandstone.

The great thickness of unsaturated material may not be due entirely to drainage of ground water into canyons. Several lines of evidence point to relative impermeability of the sandstone at many places, particularly near the land surface where water must be absorbed if it is to contribute to a ground-water reservoir. Tests by the Bureau of Reclamation of the sandstone at the Glen Canyon Dam site in Arizona, and by the Geological Survey of the aquifers at Grand Junction, Colo., show those sandstones to have a relatively low permeability. Low permeability is suggested also by several streams draining sandstone areas, which have a great volume of storm runoff during rainstorms, and very low base flow.

The rim of the Grand Canyon is formed by a cavernous limestone that also forms the surface of the plateau over an extensive area, notably the Kaibab Plateau at the north rim. This limestone is exceedingly permeable, and water from melting snow or from intense rains is absorbed by it with practically no runoff. But in extensive areas near the canyon there is no ground water in the formation. Water evidently moves downward through it into a permeable sandstone below, and probably then into deeper permeable formations. The large springs in Havasupai and Bright Angel Creeks, and the large saline spring in the floor of the canyon of the Little Colorado River, apparently mark the reappearance of the water that infiltrates into the plateau surface. Here is an exceptional case where great permeability is a handicap to ground-water development. With most of the water sinking out of range before they can reach it, the residents of the Grand Canyon National Park, and of Cameron and Flagstaff and intermediate points, now depend on small seeps or very deep wells for their supplies. To the southeast, away from the deep canyons, the sandstone is saturated, and it is the source of supply for several irrigation wells near Holbrook. Farther east, even the overlying cavernous limestone carries some water.

Little is known of the limestones in the northern part of the region. Cavernous limestone crops out in the Uinta Mountains but is at great depth under the plateau regions to the north and south, and the water in it may be saline. Cavernous limestone is also at considerable depth in the Wind River basin farther north, and it is possible that some some of the water in it may be usable.

Probably the greatest accumulations of alluvial debris in the plateau region are near the bases of the high ranges bordering the northern part of the region. The Uinta Basin, south of the Uinta Range in northeastern Utah, has received thick deposits from that range, including much

coarse debris. There are similar sites of deposition at the bases of the Wind River Mountains and the Medicine Bow Mountains in Wyoming. Although there has been little drilling in these materials, it is possible that the ground-water reservoirs are capable of moderate to large yields to wells.

The streams of the plateau region have little sand and gravel in their channels, either in depth below the stream bed or in width of flood plain. And it is likely that there are few places where wells could be developed along those channels for the purpose of draining the alluvium during low stream flow, and obtaining replenishment at flood stages.

Great Plains

Summary

EXTENSIVE semiarid to subhumid plains and plateaus east of the Rockies, extending from South Dakota to western Texas and eastern New Mexico. The region is underlain mainly by consolidated sedimentary rocks, covered by alluvial outwash from the Rockies.

The precipitation is generally sufficient only to support grazing or dry farming, and irrigation is needed for maximum crop production. In normal or wet years, wheat growing is successful in the northern part of the region, but in dry years crops are poor, or even failures, unless supplemental water is provided. A large quantity of water is stored in a sheet of permeable sand and gravel. In western Nebraska a fortunate combination of High Plains deposits and glacial outwash sand and gravel, and an extensive area of sand dunes, produce a large supply of ground water with a substantial annual replenishment. The region is traversed by a number of large rivers heading in the Rockies, and developed for irrigation and power production.

The region is one of prevailing water deficiency, under existing conditions of development. There is considerable erosion and sedimentation, and a problem of poor water quality in the south, where some of the streams cross outcrops of salt-bearing rocks. The High Plains of Texas are one of the principal areas of ground-water depletion in the United States. Water is being mined, and a forced reduction in draft is only a matter of time and of the relation of pumping cost to value of product.

Most of the major streams are susceptible to considerable additional development to achieve greater use and less waste of and damage by water. There is promise of successful development of ground-water supplies for towns, small industries, and farms even in the less favorable areas, and of much additional ground-water development in the more productive areas. Utilization of the productive ground-water reservoirs of the central area, not only for water supply but for storage of floodwater through excess irrigation, is a possibility.

Much additional study is needed—in the central area, of the interrelation of aquifers of different ages and at different levels, particularly in relation to stream flow and to movement of water beneath surface drainage divides; in the southern area, of principles of maximum economical recovery of stored water so as to derive the maximum benefit from what, in that area, is essentially an irreplacable resource, and study of possible methods of providing supplementary water, or gainful activities other than irrigation with well water.

The Great Plains is the broad belt east of the Rockies which was the site of deposition of vast quantities of sediment carried by streams from the mountains. In the geologic past these alluvial plains extended over much of eastern New Mexico and the panhandles of Texas and Oklahoma, eastern Colorado and Kansas, eastern Wyoming and Nebraska, eastern Montana, and the Dakotas. Today a large part of this vast alluvial plain has been eroded away by streams, both along its western margin near the base of the Rockies and along its eastern margin. The remnants of the original plain, known as the High Plains, generally stand well above the channels of major streams.

The Great Plains ground-water region occupies essentially the area of the High Plains. Unconsolidated sediments containing many beds of sand and gravel underlie these High Plains to considerable depth in most places. Elsewhere in the Great Plains ground water is found in consolidated sedimentary rocks, or in stream-channel or terrace deposits, or in glacial drift, as it is throughout the great central region that adjoins the Great Plains to the east. Consolidated rocks also lie under the ground-water reservoirs of loose sand and gravel in the High Plains, but there is little incentive to explore these deep deposits so long as there is an abundance of water at shallower depth.

The Great Plains ground-water region, as outlined in figure 20, includes the areas of major accumulations of sand and gravel of the High Plains, and extends from southern New Mexico and western Texas to the southern part of South Dakota. It corresponds roughly to Meinzer's Great Plains Pliocene-Cretaceous and Great Plains Pliocene-Paleozoic ground-water provinces, except that it does not adjoin the Rocky Mountains in Colorado. As outlined here, the High Plains region forms practically an island in the western part of the Unglaciated Central region.

This ground-water region crosses the drainage basins of several streams that rise in the Rockies and drain eastward toward the Mississippi River: the North Platte, South Platte, Arkansas, and Canadian Rivers. In addition, several important streams of the Mississippi River system rise within the region: the Niobrara, Republican, Smoky Hill, Cimarron, and Red Rivers. The southern part of the region is drained by the Brazos River, Colorado River (Texas

version), and some tributaries of the Rio Grande; these streams flow to the Gulf coast.

The climate of the Great Plains region is semiarid, thanks to the rain shadow of the Rockies, and the region is well adapted for wheat farming and grazing. Rainfall is commonly least near the western margin of the region and increases eastward. Particularly in the more arid western areas, irrigation is essential for cultivated crops.

Similarities to and Contrasts With the Arid Basins

The east and west descents from the Rocky Mountain chain are quite dissimilar. To the east, the Great Plains were formed by vast accumulations of sediment derived from the mountains, with some subsequent erosion. By contrast, the Colorado Pleateaus, although lower than the highest ranges of the Rockies, are still elevated enough to be the sites of intensive erosion. The debris from the mountains is not accumulating in any great quantity there.

The principal areas of accumulation of debris west of the Rockies are the intermontane valleys of the arid-basin region, some of which are filled with debris from the Rockies, others with material eroded from ranges within the arid-basin region itself. These basins, each small in extent in comparison with the Great Plains, are nevertheless the principal ground-water repositories on the Pacific slope of the continent, and thus might be considered as the western counterpart of the ground-water reservoirs of the High Plains.

N E B R A S K A
K A N S A S
O K L A H O M A
T E X A S
Aquifers capable of moderate to large yields to wells
Gravel and sand
Watercourses
SCALE
0 50 100 150 200 Miles

FIGURE 20.—*Great Plains: large ground-water reservoirs, with considerable variation in replenishment.*

The arid basins are filled mostly with debris from close at hand, because it comes from the mountains bordering the basins. By contrast, the eastern margin of the High Plains is as much as 400 miles from the Rocky Mountains, yet those mountains were the source of practically all the stream deposits underlying those plains. Most of the streams of the arid basins are relatively short and lose water rapidly as they flow across the basins, and many dry up entirely in their lower courses. The streams that have carried detritus eastward from the Rockies also may lose some water as they flow across the High Plains, but because of increasing precipitation to the east most of those streams are through flowing.

Even small canyon streams in the arid basins carry material of every size from boulders to clay particles, and those materials may be very poorly sorted, particularly if the stream flow is torrential. By contrast, the streams flowing eastward from the Rockies do not carry large fragments far from the mountains, and they can carry much of the clay size right on through the region, eventually to reach the Mississippi. As a rule, therefore, the deposits of the High Plains have a higher proportion of sand, silt, and fine gravel, and a better degree of sorting, than the valley fill of the western basins.

The water in the valley fill of the arid basins is derived largely by seepage from streams that drain the bordering mountains. In the High Plains there are relatively few places where the streams coming from the Rockies contribute to ground-water reservoirs under natural conditions, because these main-stream channels have been eroded to such depth that they are commonly lower than the regional water table. Perhaps in the geologic past some of the water now stored underground was recharged from these streams. Now those ground-water reservoirs look to precipitation upon the High Plains for most of their recharge.

Water is discharged naturally from the ground-water reservoirs of the arid basins chiefly by evaporation and transpiration. Relatively little is discharged into streams that empty into the ocean, and the amount of ground water that finally reaches the ocean is small indeed, particularly in recent years when large quantities have been pumped out of the ground-water reservoirs for man's use. In contrast, the ground-water reservoirs of the High Plains may discharge significant amounts to streams, and in some streams most of the flow comes from ground-water reservoirs. The Loup River in Nebraska is an outstanding example of a stream having fairly uniform discharge throughout the year; the ground-water reservoir in that drainage basin provides effective natural regulation of stream flow.

The Ground-Water Reservoirs

The High Plains ground-water region as shown in figure 20 includes in most places aquifers capable of yielding moderate to large quantities of water to wells. These productive aquifers occupy more extensive areas than do those in any of the ground-water regions farther west.

The conditions of occurrence of ground-water are by no means uniform throughout this extensive area, however. The water-bearing materials are stream deposits, and subject to all the variations that are characteristic of stream deposits everywhere. They include gravel, sand, silt, and clay in various degrees of sorting, and therefore with a wide range in permeability. In most places they are permeable enough to furnish at least some water to wells, and they contain abundant irregularly distributed lenses and stringers of gravel and sand that yield large quantities of good water to many wells.

The thickness of the alluvial materials is quite variable, in part because they were deposited upon an uneven, rolling surface of consolidated rocks. In the development of the smooth surface of the High Plains, as much as 700 feet of alluvium was deposited in valleys and swales of the old land surface, but alluvial materials are thin or absent over ancient hills and ridges. Also, in many places the water-bearing formations have been extensively eroded. The Canadian River has cut entirely through them and now flows upon the older impermeable rocks throughout its course from the Rockies to its junction with the Arkansas River in central Oklahoma. In extensive areas of the drainage basins of the North and South Platte, Republican, Smoky Hill, Arkansas, and Pecos Rivers, water-bearing sands and gravels are now thin or absent because of erosion.

The formations that are now important aquifers in the High Plains were once more or less continuous in a belt that extended eastward from the Rocky Mountains for as much as 400 miles. Those water-bearing formations have since been entirely removed from extensive areas. They are absent in a belt 50 to 100 miles wide along the mountain front in Colorado and New Mexico, because of erosion by tributaries of the South Platte, Arkansas, Canadian, and Pecos Rivers.

The ground-water reservoirs of the High Plains hold a tremendous amount of water. In Texas, Oklahoma, Kansas, and Nebraska they are either the most intensively developed, or they have the greatest potentialities for development, of any in those States. The High Plains region occupies only small parts of New Mexico and Colorado, but in those States, too, the ground-water reservoirs are of economic importance. The water pumped from wells in the High Plains region is nearly 10 percent of the national total. The water is generally unconfined, occurring under water-table conditions throughout most of the region.

The capabilities for perennial yield vary widely in the region; they are generally least in the southern part and greatest in the north. In most of the region the ground-water reservoirs are replenished chiefly by downward percolation of water from precipitation. In the sand hills of Nebraska the surficial materials are so permeable that large quantities of water percolate down to the ground-water reservoir, even though the annual precipitation generally is less than 25 inches (fig. 21). In many other parts of the region, notably in Nebraska and Kansas, there are similar sandy areas where the ground-water reservoir is readily recharged.

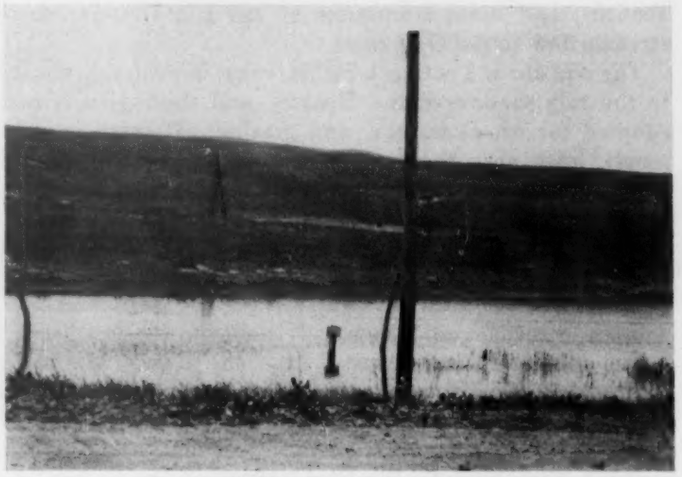

FIGURE 21.—*Water infiltrates rapidly in the sand hills of Nebraska. Numerous closed depressions have permanent lakes.*

South of the Canadian River, in the southern high plains of Texas and New Mexico, there is very little replenishment to the ground-water reservoir. There are small areas of sand dunes and some sandy soils, but impermeable material under most of the land surface impedes downward percolation, and most of the water from heavy rains stands in ponds until it evaporates (fig. 22). It has been estimated (Barnes and others, 1949) that less than half of 1 percent of the annual precipitation of about 20 inches percolates downward to the ground-water reservoir. The annual pumpage from wells in this area in 1951 exceeded 1½ million acre-feet. The rate of pumping thus is 30 to 50 times as great as the estimated recharge. Practically all the pumped water is

FIGURE 22.—*Southern High Plains of Texas. Water accumulates in ponds after heavy rains, but most of it evaporates, with negligible recharge to the ground-water reservoir.*

being taken from storage, for the natural discharge from the ground-water reservoir continues unabated (fig. 23).

The ground water under the High Plains is moving generally eastward, and more or less in the same direction as surface water, down the slope of the plains. It would be incorrect to look to the Rockies for the source of that water, however, because of the broad gap between those mountains and the western limits of the aquifers. The source of nearly all the water that goes into the ground-water reservoirs is precipitation within the High Plains region. To this general rule, however, there are at least two notable exceptions: The Platte and the Arkansas Rivers head in the Rocky Mountains, and as they flow across the Great Plains they may contribute substantial quantities of water to ground-water reservoirs along their valleys. Since the beginning of utilization of those watercourses for irrigation, the contributions to ground-water reservoirs have increased.

The watercourse of the Platte River is a major source of water for Nebraska, and is one of the best examples in the country of an area of multiple use of water (Waite and others, 1949). The waters of the South Platte in Colorado and of the North Platte in Wyoming and Nebraska have already been used extensively for irrigation before they join in the west central part of the State to form the Platte River. For more than a hundred miles downstream from this junction water is repeatedly diverted from the stream, used for irrigation, and returned to the stream (except for the quantities lost by evapotranspiration). Increasing concentration of mineral salts results from this multiple use, but fortunately the river as it flows east traverses areas of progressively increasing rainfall, and waters contributed to the watercourse in the eastern part of the State serve to dilute the water moving down the valley from the west.

In long stretches of the valley, movement of ground water is toward the river from the bordering plains; the channel of the Platte is low enough to act as a drain for the ground-water reservoir of the watercourse. In other reaches the movement of ground water is either parallel to the river or away from it. Ground water moves away from the river especially during periods when the river is at high stage, as shown by recorded stream-flow losses and by detailed contour maps of the water table in several areas. Recharge to the ground-water reservoir is chiefly from precipitation on the valley floor and adjacent plains areas, supplemented by seepage from the river and principal tributary streams and from irrigation canals and irrigated lands.

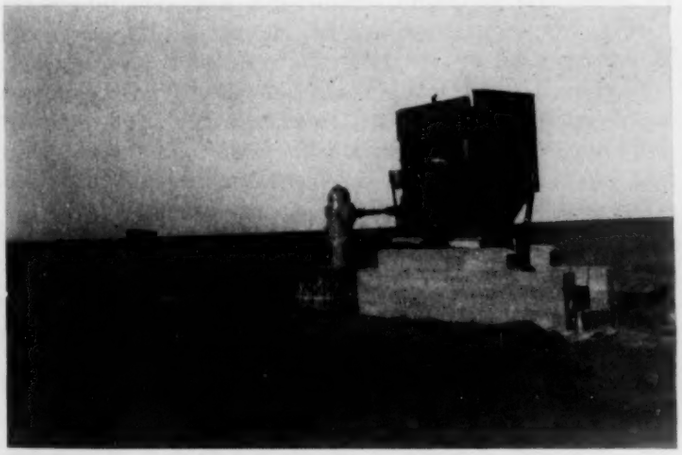

FIGURE 23.—*Irrigation pumping plant on Southern High Plains near Plainview, Tex. One of thousands that pump more than 1½ million acre-feet of water annually.*

There are about 5,500 irrigation wells in the 2,500 square miles of the Platte River Valley, and the annual pumpage is estimated to be of the order of 350,000 acre-feet. Some wells near the channel pump water that is replenished by infiltration from the stream. Others pump water that is replenished by precipitation, but the pumping nevertheless draws water that would otherwise move toward the stream and contribute to its flow. For many wells the natural supplies have been augmented by the downward percolation of irrigation water that was diverted from the stream.

Ground-water storage in the watercourse is sufficient to cushion the effects of alternating dry and wet climatic cycles. During the dry 1930's, pumping draft was greater than replenishment, and water levels declined in almost all parts of the valley. In the following decade replenishment was greater than draft, and ground-water storage by 1948 was about as great as in 1930. There are small areas of concentrated draft from wells, however, where water levels are now more than 5 feet lower than in 1930.

The Arkansas River is outstanding in the extent to which the natural flow has been modified by development of both surface water and ground water (Thomas, 1951, pp. 156–160). The headwaters in the Rocky Mountains is a major water-producing area, but the plains of eastern Colorado and western Kansas contribute relatively small quantities to the river. Under present conditions the river does not "hold its own" after it leaves the Rockies. Generally the flow is least in reaches near Garden City, Kans., where the channel has been dry for weeks at a time in the summer. The average annual flow at Garden City is only about one-third of the runoff from the mountainous headwater area, although the drainage basin is about eight times as large. Downstream from Garden City the inflow from tributaries and from ground water is so great that the annual runoff at the Kansas-Oklahoma State line is more than five times that at Garden City, and nearly twice as much as flows from the Rockies.

Diversions from the river for irrigation in eastern Colorado and western Kansas account for most of the decrease in stream flow in those areas. Pumping from wells for irrigation in the Arkansas River Valley has also caused a significant reduction in the flow of the river. Many of the wells are used to supplement surface supplies, and are pumped chiefly in dry years. The total annual pumpage doubtless fluctuates considerably, and it may approach 150,000 acre-feet in some years.

Ground-water studies along the river valley in Kansas have shown that heavy pumping of ground water for irrigation, especially between Syracuse and Garden City, has stopped the seepage to the stream that characterized that

reach under virgin conditions, and has depleted the flow to the extent that the channel often goes dry in some summers. Prior to 1925 the ground-water inflow to the stream from the adjacent plains in this reach was frequently more than enough to offset the diversions through canals and wells. In the past quarter century stream losses have been recorded every year; in most years the losses have been substantially greater than the canal diversions, and were undoubtedly caused in part by pumping from wells. Infiltration of river flow into the ground-water reservoir of the watercourse not only has replenished the water pumped for irrigation, but has been of considerable value in dissipating floods. Many floods passing Syracuse have been largely absorbed by the partly depleted ground-water reservoir near Garden City. Only the largest floods continue as far downstream as Larned, and these have greatly reduced crests. The pumping from the several hundred irrigation wells in the Arkansas Valley in Colorado doubtless has had similar effects upon the flow of the river.

Although in the present stage of development the quantity of water utilized must vary considerably from year to year, the water users in the Arkansas Valley are not entirely at the mercy of the vagaries of natural precipitation and stream flow. The John Martin Reservoir (on the river near Lamar, Colo.) can give more uniform flow from year to year than the natural stream, through hold-over storage. The ground-water reservoir along the watercourse also cushions the effects of alternate excess and deficiency of stream flow. Many wells are pumped only when water is needed to supplement inadequate stream supplies, and most wells are pumped more heavily in drought than in wet periods. That water is pumped from underground storage. At some wells the pumped water may be replaced quickly by river infiltration; at others the replacement may be delayed for several months or even several years, until the river is at higher stage, or until local precipitation is more abundant. In the absence of ground-water studies in the area, it is not possible to say where ground-water development might cause direct depletion of stream flow, and where such development might depend instead upon recharge during periods of surplus supplies; but it is likely that in many places the ground-water reservoir could be manipulated like the John Martin Reservoir, being filled during flood stages, and drawn upon in time of need.

Unglaciated Central Region

Summary

INTERIOR PLAINS and low plateaus extending from the Great Plains or Rocky Mountains on the west to the Appalachian region on the east, north of the Gulf Coastal Plain and south of the glaciated area.

This vast interior region varies widely in climate, from arid in the west to humid in the east. It overlaps on the west with the Arid Basin region, in such areas as the Pecos Valley. It includes the separated but similar Driftless Area of Wisconsin. It is characterized by consolidated sedimentary rocks that are overlain by unconsolidated sediments only in the valleys of the major streams.

The region is one of increasing precipitation and runoff from west to east. It is characterized by aquifers of rather low productivity, except for certain productive limestones and for the alluvium of major streams. Ground-water intake and discharge are not large, on the whole, and streams have low summer and fall flows.

The water problems of the region are those of general inadequacy of water supplies for all uses at reasonable cost, the situation naturally worsening toward the drier western part. There is considerable soil erosion, and problems of poor surface-water quality in the west and poor quality of ground water in scattered areas throughout. Ground water of good quality is not available at any great depth below stream level, except in certain areas of deeply buried sandstone and associated rocks. Good reservoir sites are not too abundant, yet storage of surface water is essential for large-scale uses in many parts of the region.

Experience shows that the possibilities for successful development of ground water are always improved by careful study of regional and local hydrology—in some unfavorable areas study has raised the proportion of successful wells from one out of five to better than four out of five. On this basis it appears that more—and more successful—ground-water developments are possible. Many more small-scale surface-storage developments appear to be possible. Large-scale ground-water developments by induced infiltration along the major streams appear to be feasible.

Ground-water studies that improve the chances for successful well location so far have covered only a small fraction of the region. Studies of stream-flow characteristics for use in designing economical reservoirs of small size are in only a beginning stage. Little is known about the location of deposits of permeable alluvium along the large streams where induced infiltration to wells may be possible.

The United States has a broad central area of relatively low land, bounded by the Rocky Mountain chain on the west, and by the Appalachian uplift on the east. The ground-water conditions in the northern part of this Central Lowland are determined to a considerable degree by the effects of glaciation. To the south the continental margin has been extended into the Gulf of Mexico by sedimentation through several geologic ages, and the Coastal Plain thus formed has its own characteristic conditions of ground-water occurrence. The Great Plains ground-water region, just discussed, has been formed in the western part of this Central Lowland by stream deposits from the Rockies.

The remainder of the Central Lowland has had a rather drab geologic history for the past several million years, with no glaciation, no contact with the ocean, no great accumulation of alluvium from high mountains or if such alluvium has accumulated it has subsequently been removed. Those areas have experienced only the gradational processes that go on in any land area, including erosion, transportation, and deposition of sediment by the streams of the area. The areas are grouped here as the unglaciated central region (fig. 24).

The unglaciated central region includes a large part of the Missouri River Basin in Montana, Wyoming, and the Dakotas; almost pinched out by the Great Plains in Nebraska, it broadens southward in the Arkansas and Red River Basins, and winds around the south and west edges of the Great Plains region; wasp-waisted to the east as it crosses the Mississippi, the region broadens farther east to include much of the Ohio and Tennessee River Basins and extends into Pennsylvania and New York. The region also includes the separated "driftless area" which the glaciers missed in parts of Wisconsin and Illinois.

The unglaciated central region is one of remarkable diversity. Diversity in climate, from the cold of Montana to the heat of Texas, and from the semiaridity of New Mexico to the humidity of Arkansas and Tennessee. Diversity in altitude, from near sea level in Texas to mile-high areas in Montana. Diversity in geology, with rocks ranging in age from pre-Cambrian to Recent, and with considerable variety in geologic structure, including some ancient mountain ranges. There is also considerable diversity in the characteristics of ground-water occurrence in the unglaciated central region, so that the region is eminently suitable for sub-

division into a number of more homogeneous units. Indeed, the region includes five of Meinzer's ground-water provinces (the South-Central Paleozoic, Wisconsin Paleozoic, Trans-Pecos Paleozoic, Black Hills Cretaceous, and Montana Eocene-Cretaceous provinces) and parts of three others.

However, the ground-water reservoirs of the region have some characteristics in common. Thus, all the extensive aquifers are consolidated sedimentary rocks. Generally those sediments are in flat-lying beds, but they are steeply inclined in limited areas, such as the Black Hills in South Dakota and the Ozark and Ouachita uplifts in Missouri, Arkansas, and Oklahoma. In most of the region these consolidated rocks are practically the only sources of water for wells.

Gravel and sand deposited by streams constitute the other major type of aquifer throughout the region. These aquifers are commonly more productive than the consolidated rocks, but they are restricted to the valleys or former valleys of streams, and thus are present in only a very small proportion of the total area of the region. The most productive gravel and sand aquifers are in the watercourses of perennial streams. Similar but older deposits laid down by rivers during the long history of the region are also good sources of water in some places.

Ground-Water Reservoirs in Consolidated Rocks

The sedimentary rocks of the Unglaciated Central region include a wide variety of rock types—conglomerate, sandstone, siltstone, shale, clay, coal, chert, marl, limestone, dolomite, gypsum—ranging from Cambrian to Tertiary in age.

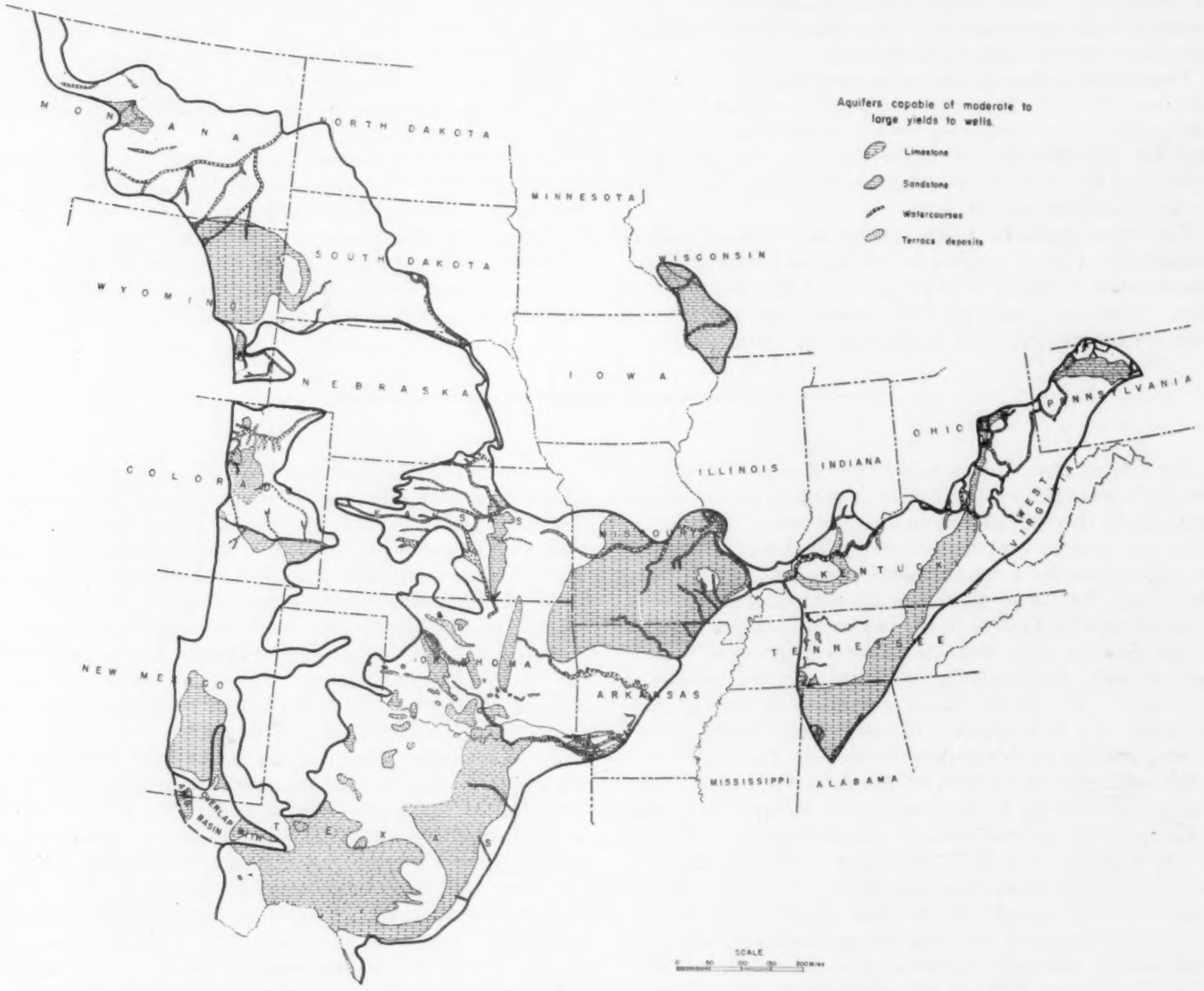

FIGURE 24.—*Unglaciated central region: especially limestone reservoirs; also some sandstone and some aquifers along streams.*

There is also a wide range in permeabilities of those rocks, and therefore a wide variation in the productivity of wells.

Almost every one of the rock types mentioned above is a source of water to wells in some part of the region. For instance, large quantities of water are pumped from irrigation wells in the Brule clay in southeastern Wyoming (the "clay" in the wells appears to be a jointed siltstone), and from cavernous gypsum in western Oklahoma. One of the least permeable rocks of the entire Nation is the Pierre shale of the Dakotas; yet some wells obtain water from zones of brittle shale where weathering and fracturing have developed greater-than-usual permeability in the rock. In general, the relatively impermeable rocks provide supplies sufficient only for domestic or stock use, and they are important only in areas that lack permeable water-bearing rocks. In quantity, the water yielded by such rocks is an insignificant part of the total yielded by wells in the region.

Of all the consolidated rocks of the region, limestone forms by far the most productive and the most extensive ground-water reservoirs. Important limestone reservoirs of the region are in the Roswell Basin in New Mexico; the Edwards Plateau in Texas; the Ozark area in Missouri, Arkansas, Oklahoma, and Kansas; the Black Hills area in South Dakota and Wyoming; and the Tennessee Valley in Alabama and Tennessee. More than a dozen of the Nation's largest springs issue from these reservoirs, eight of them in the Ozark area alone. Some wells in these reservoirs, too, are famed for their large production. Twenty-five years ago the title of largest flowing well in the country was claimed for an irrigation well in the Roswell Basin, on the basis of a yield of 8½ million gallons a day. The title has since passed to an artesian well at San Antonio, Tex., which can produce about 25 million gallons a day from the limestone under the Edwards Plateau.

About 120,000 acres of land is irrigated in the Roswell Basin of New Mexico, almost entirely from wells. The first artesian well was drilled in 1891, and the great development of large flowing wells for irrigation began about 1903. Artesian pressures dropped markedly during the next decade, and new development was practically stopped by 1915. By 1925 the area in which artesian flows could be obtained had shrunk from the original 660 to 425 square miles, and many farms in the outskirts of the valley had been abandoned (fig. 25) (Fiedler and Nye, 1933).

The New Mexico ground-water law was intended primarily to protect the water resources of this basin from exhaustion, although the regulatory procedures are applicable to all ground-water reservoirs in the State. The statute gives the State engineer authority to safeguard the basin's water supplies against overdevelopment and waste. In the past two decades waste from wells has been practically eliminated, and no new water rights have been granted for the artesian basin. In recent years the withdrawal by wells from that basin has been of the order of 210,000 acre-feet a year. Partly because of control measures, but undoubtedly with considerable assistance from exceptionally heavy precipitation in 1941, the artesian pressures in wells were generally higher in the winter of 1942 than they had been since 1926. They dropped nearly 12 feet in the succeeding 7 years, and have reached their lowest stages of record in the summers of the last few years.

Overlying the artesian basin is a shallow ground-water reservoir in alluvium, replenished in large part by upward leakage from the artesian reservoir and by downward percolation from irrigated lands (Morgan, 1938). Little water was pumped from this shallow reservoir before 1927, but when further drilling of artesian wells was stopped there was a marked acceleration in development, and by 1937 the shallow reservoir was also closed to further permits except for replacement wells. In recent years the pumpage from shallow wells has been about 120,000 acre-feet a year. In part, this development represents salvage of water that would otherwise be discharged by evapotranspiration or by seepage into the Pecos River, and a reuse of water that had been drawn from the artesian reservoir and applied for irrigation. But pumping from the shallow reservoir has lowered the water levels by 20 feet or more in an area of 65 square miles, and the upward leakage from the artesian reservoir probably has increased as a result.

The wise regulation of the development of the basin has been shown to require an adequate foundation of hydrologic data, in order to achieve maximum utilization of the water resources and protect the holders of established rights. Present information suggests that total draft on the combined reservoirs may still be in excess of average replenishment, but it may be possible to bring the system more nearly into balance by salvaging some of the water still being lost by natural discharge. On the other hand, some outflow to the Pecos River must be permitted to continue, both to meet the established rights to water downstream and as a means of disposal of mineral salts from the Roswell Basin.

One of the most productive ground-water reservoirs in Texas underlies the Edwards Plateau and the adjacent part of the Gulf Coastal Plain. Relatively few wells tap this reservoir, but some of those wells have exceptionally large capacity. Most of the discharge from the ground-water reservoir is from springs, of which five have average discharges ranging from 90 to 300 cubic feet per second. The total spring discharge is estimated to exceed 800 million gallons a day. The ground-water reservoir is replenished in part by seepage from such streams as the Nueces, Frio, Sabinal, and Medina Rivers as they cross the outcrop of the limestone. The ground-water reservoir serves to stabilize the flow of these streams by absorbing water, especially during floods, and releasing it at more nearly constant rates from springs.

The ground-water reservoirs of the Ozark region yield water to artesian wells in Kansas and Oklahoma, where the limestones are deeply buried, as well as in Missouri, nearer the outcrop area. These limestones also give rise to several very large springs. The characteristics of discharge from some springs are evidence not of large reservoir capacity but rather of underground drainage equivalent to the subsurface storm flow from some mountain forests. The discharge

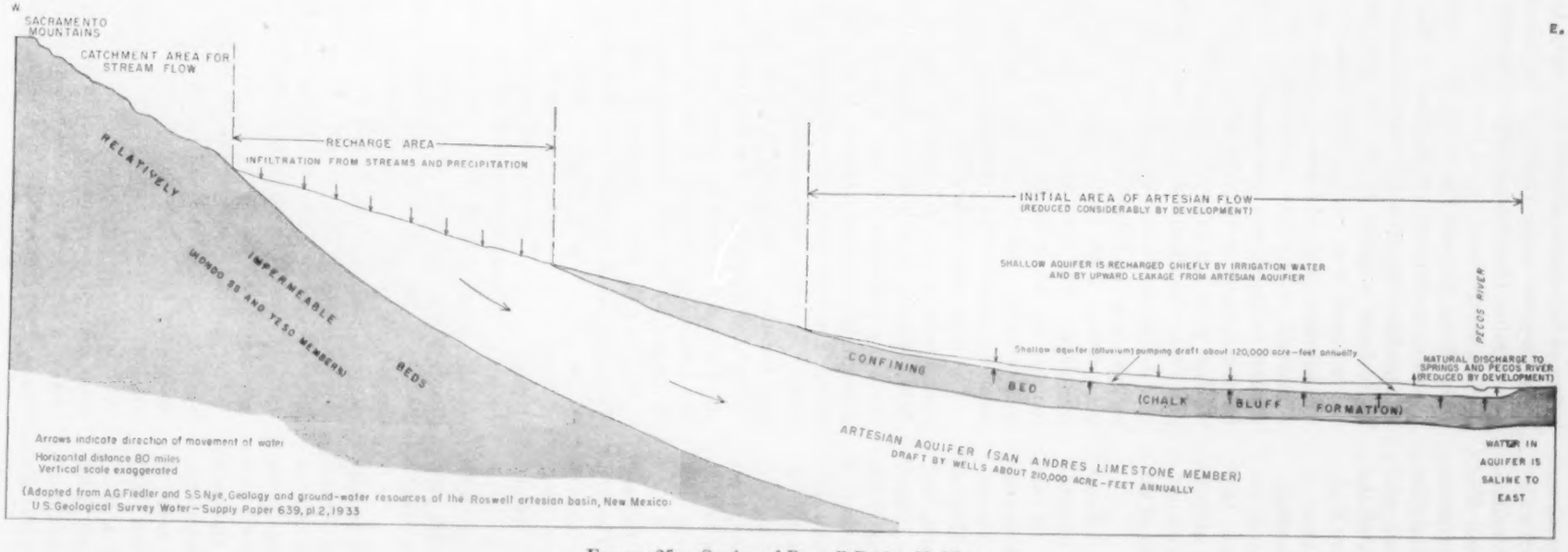
W.
SACRAMENTO MOUNTAINS
E.
CATCHMENT AREA FOR STREAM FLOW
RECHARGE AREA
INFILTRATION FROM STREAMS AND PRECIPITATION
RELATIVELY IMPERMEABLE BEDS
(RONDO SS AND YESO MEMBERS)
INITIAL AREA OF ARTESIAN FLOW
(REDUCED CONSIDERABLY BY DEVELOPMENT)
SHALLOW AQUIFER IS RECHARGED CHIEFLY BY IRRIGATION WATER AND BY UPWARD LEAKAGE FROM ARTESIAN AQUIFER
PECOS RIVER
Shallow aquifer (alluvium) pumping draft about 120,000 acre-feet annually
NATURAL DISCHARGE TO SPRINGS AND PECOS RIVER (REDUCED BY DEVELOPMENT)
CONFINING BED (CHALK BLUFF FORMATION)
ARTESIAN AQUIFER (SAN ANDRES LIMESTONE MEMBER)
DRAFT BY WELLS ABOUT 210,000 ACRE-FEET ANNUALLY
WATER IN AQUIFER IS SALINE TO EAST
Arrows indicate direction of movement of water
Horizontal distance 80 miles
Vertical scale exaggerated
(Adapted from A.G. Fiedler and S.S. Nye, Geology and ground-water resources of the Roswell artesian basin, New Mexico: U.S. Geological Survey Water-Supply Paper 639, pt. 2, 1933

FIGURE 25.—*Section of Roswell Basin, N. Mex.*

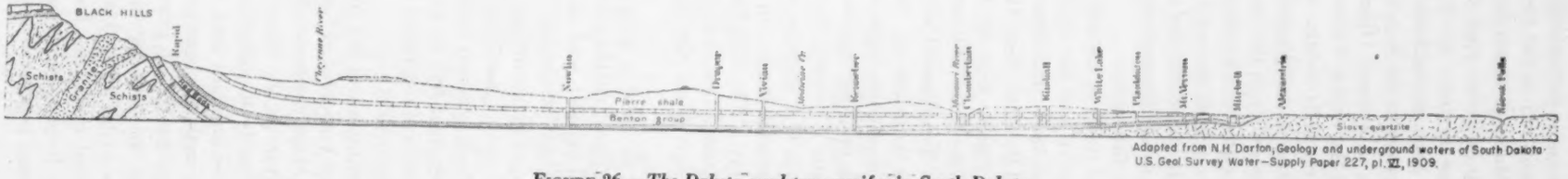
BLACK HILLS
Schists
Schists
Pierre shale
Benton group
Sioux quartzite
Adapted from N.H. Darton, Geology and underground waters of South Dakota: U.S. Geol. Survey Water-Supply Paper 227, pl. XI, 1909.

FIGURE 26.—*The Dakota sandstone aquifer in South Dakota.*

fluctuates considerably in response to precipitation, and the water may carry appreciable quantities of sediment. Thus, these springs appear to be the outlets of underground streams having characteristics similar to those of surface water in other areas.

The cavernous limestone of the Black Hills of South Dakota can be seen in the Wind Cave National Monument, and streams draining the Black Hills lose appreciable quantities of water as they cross its outcrop areas. Where that water reappears at the surface is not yet known with any certainty.

Sandstones are also important aquifers in many parts of the Unglaciated Central region. The Dakota sandstone is the well-known deep artesian aquifer of the Dakotas, and it is also tapped by wells in several other States (figs. 26, 27, and 28). Most of the wells that obtain water from that sandstone are in the glaciated part of the Dakotas. Other sandstone aquifers are tapped by wells, notably in various parts of Texas, Oklahoma, Kansas, and Colorado; and also farther east, in Wisconsin, Pennsylvania, and Ohio.

Many of the consolidated rocks of the Unglaciated Central region hold water that is too highly mineralized for use, and some discharge saline water into streams. Salt springs in central Kansas and Oklahoma are factors in the poor quality of water in the Arkansas River, and acid waters draining from coal mines in Pennsylvania are bad for several tributaries of the Ohio River. Most of the sedimentary rocks are of marine origin, and in many places they contain fresh water only within a few hundred feet, and perhaps only a few feet, of the land surface. Saline water encountered at greater depths has probably been in the rocks since their original deposition, or at least since the last submergence by the sea many millions of years ago.

Watercourses and Terrace Deposits

The ground-water reservoirs in the gravel and sand of stream valleys are relatively small in volume but may be exceedingly productive. A large proportion of this alluvial material is likely to be saturated at all times, but the upper part may be saturated only in times of flood or of heavy precipitation (these commonly occur together), and the water then drains out slowly to the stream during lower stages. Under natural conditions these ground-water reservoirs thus help to regulate the flow of streams, reducing flood crests by absorbing water and then discharging that water to increase the low flow of the stream. Pumping from wells can increase the effectiveness of the ground-water reservoir in stream regulation, if that pumping drains materials that will absorb water during the next flood (fig. 27).

Most of the alluvium is permeable enough to yield domestic supplies to dug wells, but only the gravel and sand beds

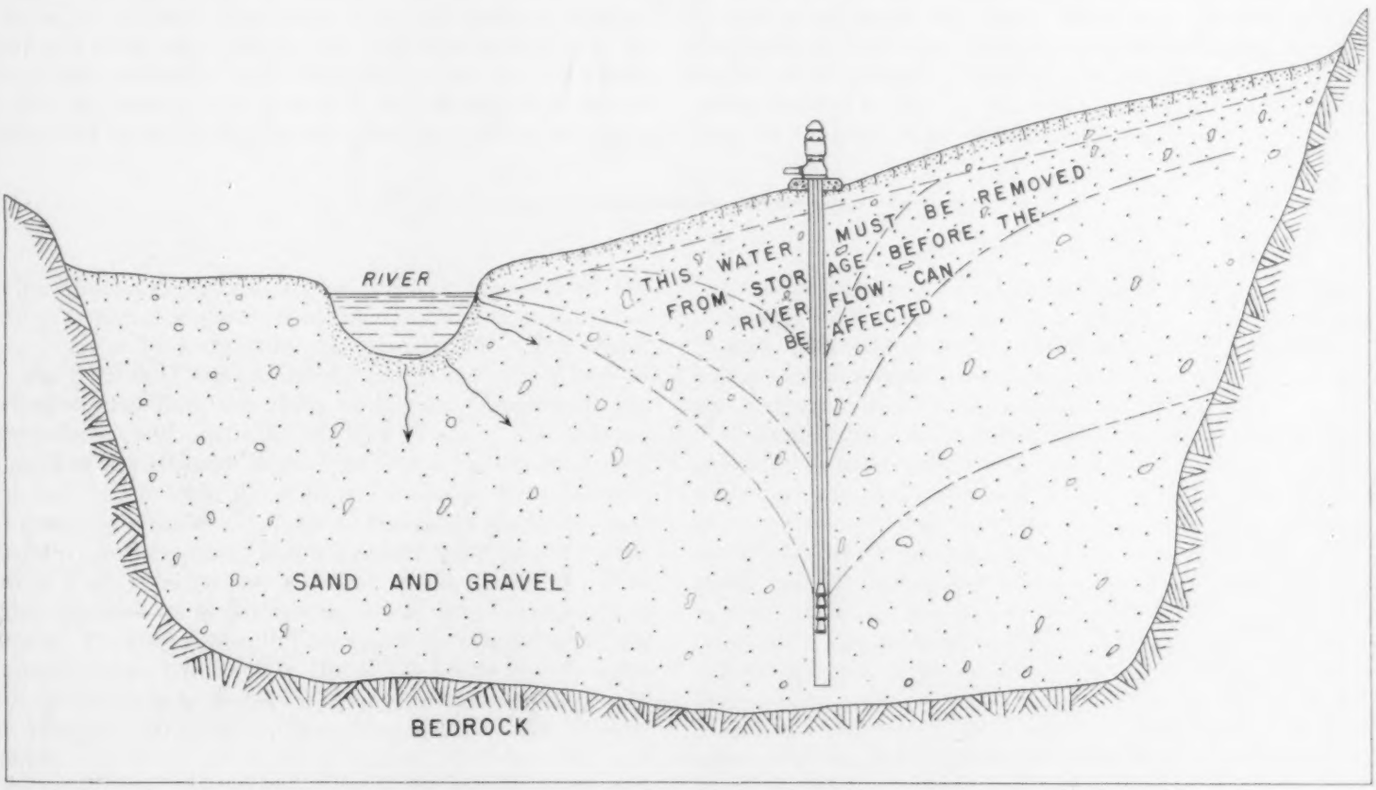

FIGURE 27.—*River infiltration. Diagram showing how a pumped well diverts ground-water underflow and induces infiltration from a stream when geologic conditions are favorable. Under such conditions exceptionally large ground-water supplies can be developed.*

yield large quantities of water. Such aquifers constitute only a minor proportion of the total alluvium in most streams, and some valleys seem to lack any appreciable quantities of coarse detritus. But gravel and sand have accumulated in considerable quantities in certain reaches of many streams. Conditions have been especially favorable near the north boundary of the unglaciated region, where the melting of continental glaciers once formed large streams capable of moving and sorting very coarse debris. This outwash is found in many valleys beyond the limit of glaciation. The ground-water characteristics of these watercourses are similar to those of watercourses in the glaciated region.

The ground water along some watercourses may be inferior in quality, owing to infiltration from rivers carrying waters of poor quality. That along the Arkansas River in Oklahoma and Arkansas is an example.

Some gravel and sand beds deposited by streams long ago now form terraces that may be scores or even hundreds of feet above present stream channels. In Oklahoma and Texas such terrace deposits constitute ground-water reservoirs which are replenished largely by local precipitation. There are also numerous gravel terraces in Montana, but the gravels in many of them are not saturated, probably because any water that percolates into them drains out with equal ease.

Glaciated Central Region

Summary

THIS REGION extends from the Rocky Mountains on the west to the Appalachians on the east. Otherwise similar to the unglaciated region to the south, it is distinguished by a sheet of glacial drift that ranges from small to very large in thickness, permeability, and underground-storage capacity.

To the extent that the glacial drift is thick and permeable, the region is characterized by high potential infiltration, large underground-storage capacity, well-sustained stream flow, and large ground-water supplies, both in the glacial drift and in the bedrocks which it feeds. The thickest and most permeable drift is found in Michigan and parts of Indiana, Ohio, Illinois, Wisconsin, Iowa, and Minnesota. In the other parts of the region the drift is generally thinner and less effective as a reservoir, and the hydrology is similar to that of the unglaciated region to the south. Even in those parts of the region, however, there are channels of glacial outwash along which good deposits and large ground-water supplies are found.

Water problems, on the whole, are not as serious as in some other regions. The region is one of intensive agricultural and industrial activity, and local shortages of ground water have arisen in some industrial communities. Some of these shortages, such as that in the Chicago area, are of substantial economic importance even though a large supply of water is available from surface sources. Especially in the northwestern part of the area, there are places where the drift is so clayey that even small supplies are not easy to get and many communities have difficulty obtaining enough water at an economical cost. Pollution of streams by sediment, industrial and domestic wastes, and acid coal-mine drainage is serious, especially in the East.

Because surface runoff is prevailingly high and well sustained, ground-water development generally interferes little with stream flow, and much greater ground-water developments are possible than have been made so far, so long as the developments are made where the water is. Most problems of shortage are local and economic, and can be solved by careful planning and intelligent, coordinated development. The outlook is especially promising for supplemental irrigation from wells and streams to provide small quantities of water at critical times, resulting in greater agricultural security and in greatly increased crop yields.

In no single State of the region is hydrologic knowledge adequate as a basis for safe, economical planning of future water developments. The need for data is especially great because of the large-scale, costly water developments made in the past and to be made in the future to support great agricultural and industrial enterprises. Substantial programs of study are now under way in most of the States, but those in some States need to be strengthened greatly.

The Glaciated Central region includes the part of the Nation's central lowland which at one time or another has been overrun by continental glaciers (fig. 29). The region extends from the Canadian border southward to this limit of glaciation, and from the plains of western Montana to the Adirondacks and Catskills of New York. The present channel of the Missouri River from Great Falls to St. Louis, and that of the Ohio River from Pittsburgh to its mouth, are generally close to this limit of maximum glaciation, and nowhere are they more than a hundred miles from it; their positions are in large part an effect of the glaciation. The region includes all of Minnesota, Iowa, and Michigan, and parts of 12 other States. The region also includes all the drainage basins tributary to the Great Lakes and to Lake Winnipeg in Canada, as well as parts of the drainage basins of the Missouri, Mississippi, Ohio, Susquehanna, and Hudson Rivers.

As to climate, the entire region is far enough north and far enough from any ocean to have cold winters and warm summers with occasional "heat waves." The Montana-Dakota part of the region, however, receives less precipitation than areas farther east, and depends upon dry farming and irrigation as standard agricultural practices.

Ground-water conditions throughout the Glaciated Central region have been considerably modified from those that prevailed prior to glaciation, and because of those modifications the region is different in many respects from the region to the south, which was not glaciated. In most of the region the preglacial surface was formed by consolidated sedimentary rocks, as in the region to the south; but in most of Minnesota and parts of northern Michigan and Wisconsin, crystalline and metamorphic rocks formed the preglacial land surface. The region includes the North Central Drift-Paleozoic, Superior Drift-Crystalline, Dakota Drift-Cretaceous, and Northwestern Drift-Eocene-Cretaceous provinces as outlined by Meinzer.

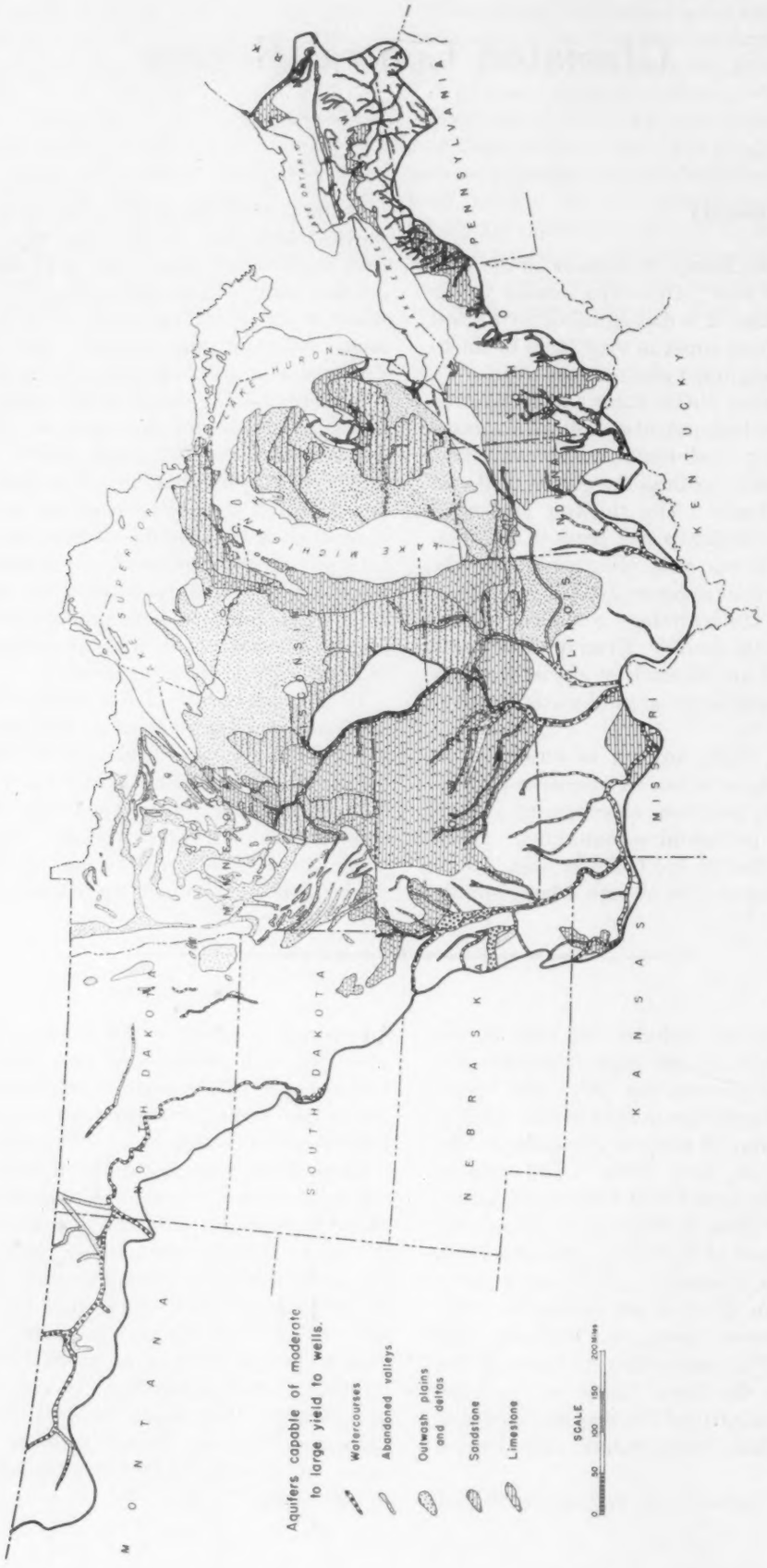

FIGURE 28.—*Glaciated central region: many important watercourses, other storage facilities of glacial origin, and extensive sandstone aquifers.*

Consolidated Rocks Similar to Unglaciated Area

The continental glaciers rode over a surface composed predominantly of sedimentary rocks, which are now buried beneath the glacial drift except in a few places. As in the unglaciated region to the south, several of these rocks form important ground-water reservoirs. Sandstones are the most extensive and productive aquifers among the consolidated rocks in the glaciated region. Limestones are generally less abundant and less productive of ground water than in the region farther south, though good locations are by no means lacking.

The Dakota sandstone in the western part of the region is one of the best-known aquifers in the country (Wenzel and Sand, 1942). It forms a nearly continuous bed across the Dakotas and extends into Minnesota, Iowa, Nebraska, Wyoming, and Montana. In most of that area water is confined in the sandstone under artesian pressure. Sixty years ago some wells flowed more than 4,000 gallons per minute and some had sufficient artesian pressure to raise the water more than 400 feet above the land surface. In succeeding years the artesian pressure in the areas where wells are concentrated has declined until many wells have stopped flowing, and few wells now flow more than 10 gallons per minute (figs. 29, 30). The discharge from wells has caused the pressure head to decline several feet in areas as much as a hundred miles west of the area of artesian flow. But the recharge area for the sandstone is still farther west, and there has been no appreciable decline of the water table there. The sustained yield of this aquifer, obviously far less than the initial yield to wells, is limited not by the rate of replenishment in the recharge area, but by the rate at which water can move eastward through the sandstone from that recharge area—a rate that has been estimated in some places to be less than 100 gallons per minute in each mile of width of the aquifer. The former great yields of wells might be regarded as coming practically from dead storage that cannot economically be filled again.

Sandstone aquifers extend also through large parts of Iowa, eastern Minnesota, Wisconsin (including the Driftless area), northern Illinois, and Michigan. In many places the aquifers are deeply buried and water is confined in them under artesian pressure. In this humid area the largest users of ground water are municipalities and industries, and draft from wells is therefore concentrated in urban areas. Among the cities that draw heavily upon sandstone aquifers are Chicago, Joliet, and Rockford, Ill.; Milwaukee, Madison, Fond du Lac, and Green Bay, Wis.; Lansing, Jackson, and Battle Creek, Mich.; and Minneapolis and St. Paul, Minn.

At several of these cities, particularly where water is confined in the sandstone, the concentrated draft has caused a progressive decline in artesian pressure. A notable example is the Chicago area, where on the average 65 million gallons a day is pumped from sandstones 800 to 2,200 feet deep (Chicago area water supply, 1950). Until 1900 most wells in these sandstones flowed by artesian pressure, but the pressure has declined more than 400 feet in some areas, and pumping lifts in the Chicago area are now among the greatest to be found in the eastern half of the country. The areas in which artesian pressures have been lowered significantly extend at the most 30 to 40 miles out from the centers of heavy pumping. It is unlikely that pumping has induced any appreciable increase in rate of flow from the recharge area, which is more than 80 miles from Chicago. The declining levels show that pumping has been in excess of the rate of transmission through the sandstone, and partly at

FIGURE 29.—*Artesian well at Woonsocket, S. Dak. in 1895. Yield, about 1,150 gallons per minute.*

FIGURE 30.—*Same well in 1947, flowing 30 gallons per minute.*

the expense of artesian storage. This rate of transmission must set the ultimate limit of use of water from the aquifer in the Chicago area, unless methods can be developed for putting water into the aquifer within the area where it is to be used. Because the ground water is used chiefly for cooling, and because Lake Michigan in the winter is cold enough for this purpose, winter recharge through wells by lake water might be a feasible means of using the storage facilities of the aquifer.

In other cities, of which Rockford (Ill.), Madison, and Minneapolis are examples, artesian pressures are fairly stable under present conditions of withdrawal, although water levels in wells are substantially lower than in the early stages of ground-water development. Some decline of water level or artesian pressure is inevitable wherever water is diverted from its path toward points of natural discharge and is induced to move instead toward wells. In the places mentioned above, it appears that a new balance has been established, in which the existing wells are an integral part of the ground-water circulatory system. Water now moves toward the wells at rates comparable to the withdrawal, and the wells thus appear to be on a sustained-yield basis.

The limestones in these Northern States are only moderately productive, but are important sources of water in some areas. Several towns in Ohio, Indiana, Illinois, and Iowa obtain their municipal supplies from limestone. According to studies at some of these towns, the limestone contains permeable zones in such places as the flanks of ancient coral reefs, or along certain joints, but may not have continuous permeability over extensive areas. Many wells tapping these constricted aquifers have moderate to high initial yield but have not been able to sustain that yield.

In the vicinity of Lake Superior, sedimentary rocks are absent and crystalline or metamorphic rocks appear at the surface or immediately under the glacial drift. The prospects for productive wells in these rocks are poor, for one must find fractures large enough to carry the water needed. Nevertheless, the pore space in several acres is sufficient to yield considerable water, as shown in mines in the iron ranges of northern Michigan. Ground water enters some mines rapidly enough to be troublesome, and expensive pumping systems are required to remove it.

The Effects of Glaciation

A characteristic common to the entire Glaciated Central region is that glaciation has modified the ground-water conditions. Those modifications, however, have been quite diverse in various parts of the region. In the few places where bare rocks now crop out (notably the crystalline rocks of the Lake Superior region), and perhaps in other places, it is likely that surficial materials of various permeabilities have been removed by the eroding action of the glaciers.

But in this country the glaciers were chiefly engaged in depositing the debris that had been picked up in Canada, and thus they formed the mantle that is collectively termed "glacial drift." That drift is very thin in some places, and hundreds of feet thick in others. In many places the glacial drift is permeable enough to have become an important source of water for wells and springs. In many other places the drift is an unsorted mass of rock flour and coarser particles, so impermeable that very little water can move through it. Thus glaciation has modified ground-water conditions by deposition both of permeable materials that form ground-water reservoirs, and of impermeable materials that prevent subterranean movement of water.

The bulk of the glacial drift is till, deposited directly by the melting ice, and entirely unassorted. It is essentially impermeable if it includes any appreciable proportion of clay-size particles or rock flour. This impermeable material has had an important effect upon the natural facilities for storage of water, largely because the glaciers have dropped it without much regard for the drainage pattern that existed before the glacial advances. Throughout the glaciated country, and especially in Minnesota and Wisconsin, there are thousands of undrained depressions, and many are now occupied by lakes. Man, in providing drainage outlets for these depressions, has reduced the natural water-storage facilities; and in some instances the result has been to increase the flood hazards of the streams into which the outflow from those depressions has been turned. It is likely also that in some places the glacial till provides a less permeable land surface than the preglacial surface, and the effect of glaciation has been to decrease the infiltration and increase the storm runoff in those places. On the whole, however, the glacial mantle permits greater infiltration and storage than existed before glaciation.

In some places the glacial till is composed chiefly of sandy material and thus is fairly permeable. Especially in the northern part of the Lower Peninsula of Michigan, but also in parts of Wisconsin and Illinois and locally in other States, the glacial till forms a ground-water reservoir capable of yielding moderate or even large supplies to wells.

The gravelly and sandy deposits of streams that issued from the ice are the great water bearers of the glacial drift (fig. 85). They occur in abundant irregular lenses and stringers of gravel and sand intimately intermingled with the till; in deltas formed in glacial lakes; in outwash aprons that extended out from the edges of the several ice sheets; and in valley trains deposited for many miles along the streams that headed in the ice sheets.

The gravel and sand intermingled with the till generally form thin, discontinuous bodies, but deposits are numerous enough in many places to be encountered in many drilled wells, where they yield reliable supplies, protected from pollution to some extent by overlying till. The sediments deposited in glacial lakes are prevailingly of fine texture, but sandy materials are common near the shore lines of the ancient lakes. Notable among these are the deltas of glacial Lake Agassiz in eastern North Dakota, and the sands above the present shore line of Lake Michigan (figs. 31 and 32).

The outwash aprons are generally large deposits of coarse

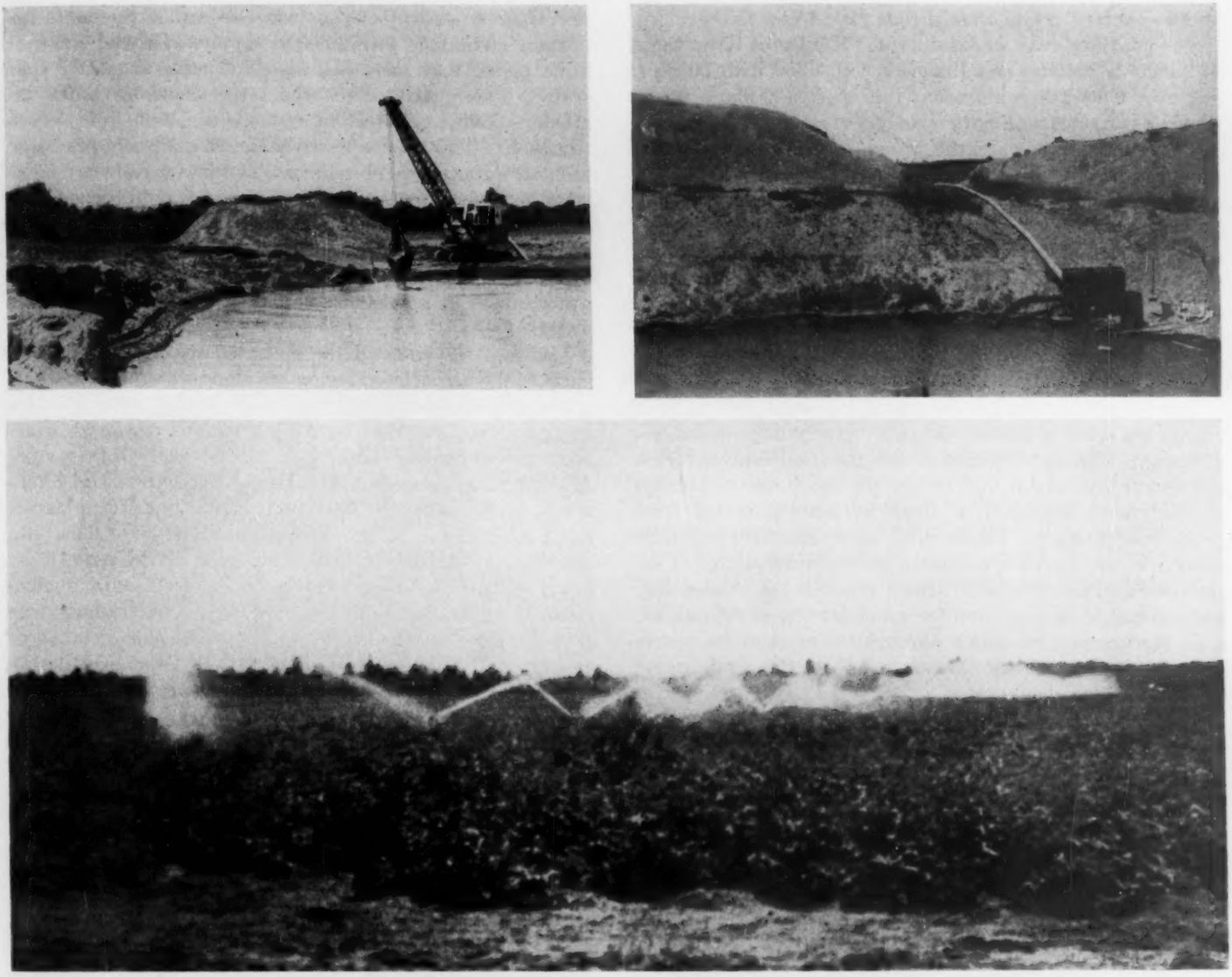

FIGURE 31.—*Irrigation with ground water from glacial outwash near Antigo, Wis. (Top left and right) Excavating a pit, and pumping; and (lower) irrigating potatoes. (Photos by F. C. Foley, U. S. Geological Survey.)*

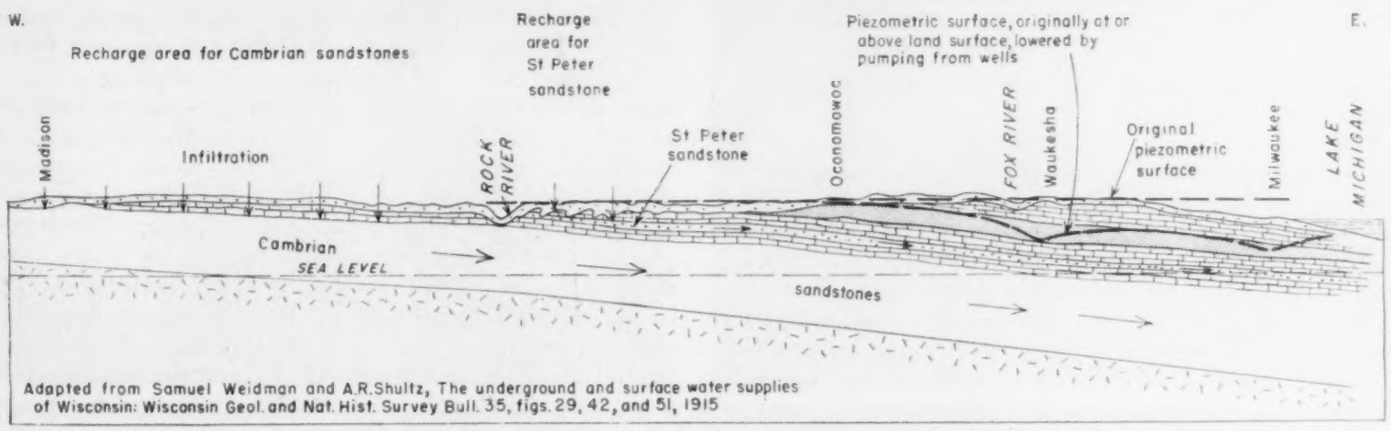
W.
Recharge area for Cambrian sandstones
Recharge area for St Peter sandstone
Piezometric surface, originally at or above land surface, lowered by pumping from wells
E.
Madison
Infiltration
ROCK RIVER
St Peter sandstone
Oconomowoc
FOX RIVER
Waukesha
Original piezometric surface
Milwaukee
LAKE MICHIGAN
Cambrian sandstones
SEA LEVEL
Adapted from Samuel Weidman and A.R. Shultz, The underground and surface water supplies of Wisconsin: Wisconsin Geol. and Nat. Hist. Survey Bull. 35, figs. 29, 42, and 51, 1915

FIGURE 32.—*Section from Madison to Milwaukee, Wis. Pumping at Milwaukee and Waukesha has lowered the artesian pressure 300 feet or more. This has increased the rate of movement through aquifers from distant discharge areas, but that rate is still less than the pumping draft at the two cities. Recharge at Madison, however, is sufficient to balance the draft.*

and well-sorted gravel or sand that yield water freely and in large quantities. As an example, the Kankakee River basin in northern Indiana and Illinois is well filled with outwash gravels. Outwash is abundant but spotty at many places near the moraines that mark the edges of ice sheets.

The valley trains are the ground-water reservoirs that produce the greatest quantities of water to wells in the glaciated region and are, therefore, among the most important of aquifers. These occupy the watercourses of present streams, as well as some valleys no longer occupied by streams.

Watercourses and Abandoned Valleys

Throughout the Nation the gravel and sand beds in river valleys are some of the best sources for very large quantities of water. The watercourses of the glaciated central region are among the best in the country for this purpose, because of the gravel deposited in them by waters melted from continental glaciers. These valley trains extended for many miles from the ice front, and many go beyond the limit of the glaciated region. The Ohio River, which is the outstanding watercourse of the country for ground-water development, is in the unglaciated region throughout most of its course from Pittsburgh to the Mississippi, but its deep gravel deposits are glacial outwash.

The eastern part of the glaciated central region is one of the most densely populated areas of the country. Water has been a very important factor in the development of the urban centers of the region: six of the largest cities (Chicago, Detroit, Cleveland, Buffalo, Milwaukee, and Toledo) are along the shores of the Great Lakes, where they have vast reservoirs of fresh water. Most of the other large cities (Pittsburgh, Cincinnati, Louisville, St. Louis, Kansas City, and Minneapolis) are along the largest rivers; admittedly, the water was used chiefly for transportation in their early history, but abundant water supply has been a key factor in the location of industries and, therefore, in the continued growth of those cities. The other large cities, and nearly all the medium-sized cities, are along streams that may be too small for navigation but are otherwise available for satisfying the water requirements of the communities and their industries.

The ground water in a watercourse is obviously not the only available water, for surface water also is generally at hand. In many instances the ground water is not even an additional supply, for if it is pumped out it is soon replaced by infiltration from the river. Wells are drilled along watercourses because the ground water has certain advantages over surface water, insofar as use is concerned. The temperature of ground water is more constant and in particular it does not rise to the tepidity of most surface waters in August; this is an important advantage where the water is to be used for cooling. Ground water is less likely to be bacterially polluted than surface water, and wells can be developed so as to yield bacteria-free water; this is an important advantage in municipal supply. Ground water in some places may have less dissolved mineral matter than surface water; and, even where the dissolved solids are greater, their concentration is more constant from season to season. This may be an advantage in treatment processes. Ground water is free of sediment, and few streams are equal to it in this respect. Ground water is a more dependable source of supply than streams, particularly if there are large fluctuations in stream discharge. These advantages have been the chief reasons for selection of ground water along watercourses as a source of supply in preference to surface water.

Many of the cities of the glaciated region and adjacent parts of the unglaciated region are along watercourses where gravel and sand beds yield large quantities of water to wells. Pumpage has exceeded 25 million gallons a day at Binghamton and Schenectady, N. Y.; Pittsburgh, Pa.; Dayton, Akron, Canton-Massillon, Hamilton-Middletown, and Chillicothe, Ohio; Louisville, Ky.; Indianapolis and Terre Haute, Ind.; Kalamazoo, Mich.; Peoria and East St. Louis, Ill.; Des Moines and Sioux City, Iowa; and the Kansas Citys. Many wells yield large supplies which are readily replenished by infiltration from the river; this is particularly true of wells close to the river banks, where the distance of underground travel is least (fig. 33). Wells at greater distances from the river may be replenished by percolation of precipitation in the vicinity, or they too may receive replenishment from the river, but more slowly and less abundantly. Thus wells distant from the river may be at a decided disadvantage so far as quantity of sustained yield is concerned, for that sustained yield is determined by the transmissivity of the rock materials between the stream and the well.

Even though watercourses as a rule offer exceptional opportunities for ground-water recharge from streams, there are many instances of "failing water supplies" in specific localities along watercourses. In Louisville during World War II, water levels in wells dropped at an alarming rate until the users cut back their pumpage from 63 to 40 million gallons a day, and some users recharged the ground-water reservoir with treated river water from the public mains during the winter. Studies since the war (Rorabaugh, 1948) have shown that wells could be constructed along a 7-mile reach of the Ohio River so as to give a sustained yield of more than 250 million gallons a day—four times the pumpage that caused the crisis in World War II. And at Pittsburgh difficulties have developed in the Golden Triangle business district because of pumping for air conditioning. There the ground-water reservoir is recharged each spring during high stages of the river, but the aquifer is so thin that the storage is inadequate for the heavy pumping during the summer, and some wells are practically dry by August (Adamson, 1949). Des Moines depends for its municipal supply upon a relatively thin aquifer also (Maffitt, 1943), and for many years has supplemented the natural replenishment by artificial means (fig. 34) with excellent results.

Some of the valleys that were occupied by rivers draining the ice sheet have since been abandoned by their streams. An example is the broad channel now occupied by the Chicago drainage canal, but formed by a river that drained Lake Michigan into the Mississippi until the glacial block in the St. Lawrence River channel melted away. The valley trains in some of these abandoned valleys are as large and as permeable as many of those along present rivers, and they may be excellent ground-water reservoirs. The sustained yield of those reservoirs, however, may be far less than the large quantities of ground water available along watercourses by river infiltration.

Most of Ohio's ground-water difficulties are concentrated in one of these abandoned valleys north of Cincinnati. Mill Creek Valley looks like and formerly was the Ohio River Valley, but it is now occupied only by Mill Creek, which is generally of wading size (fig. 35). The valley is occupied by many industries, and most depend upon wells for their water supplies. Pumpage is more than 15 million gallons a day on the average. At the towns of Lockland and Sharonville water levels in wells have declined somewhat because of pumping, but Mill Creek, though small, provides considerable recharge during floods, and the situation is not critical. Farther south, though, the aquifer was buried by thick clays that prevent replenishment by downward percolation. At Carthage, Ivorydale, and Norwood, water levels have been declining progressively for half a century. They are now as much as 80 feet lower than in 1900, and in some places less than one-third of the aquifer is still saturated (Bernhagen and Schaefer, 1947).

Although the ground-water reservoir of Mill Creek Valley is evidently inadequate to meet current demands, it is still a place where a large volume of water can be stored. If the Ohio River or another body of surface water is eventually selected to serve the water needs of the valley, the industrial need for cool water might well be served by taking water from the river in the winter and storing it underground for year-round use.

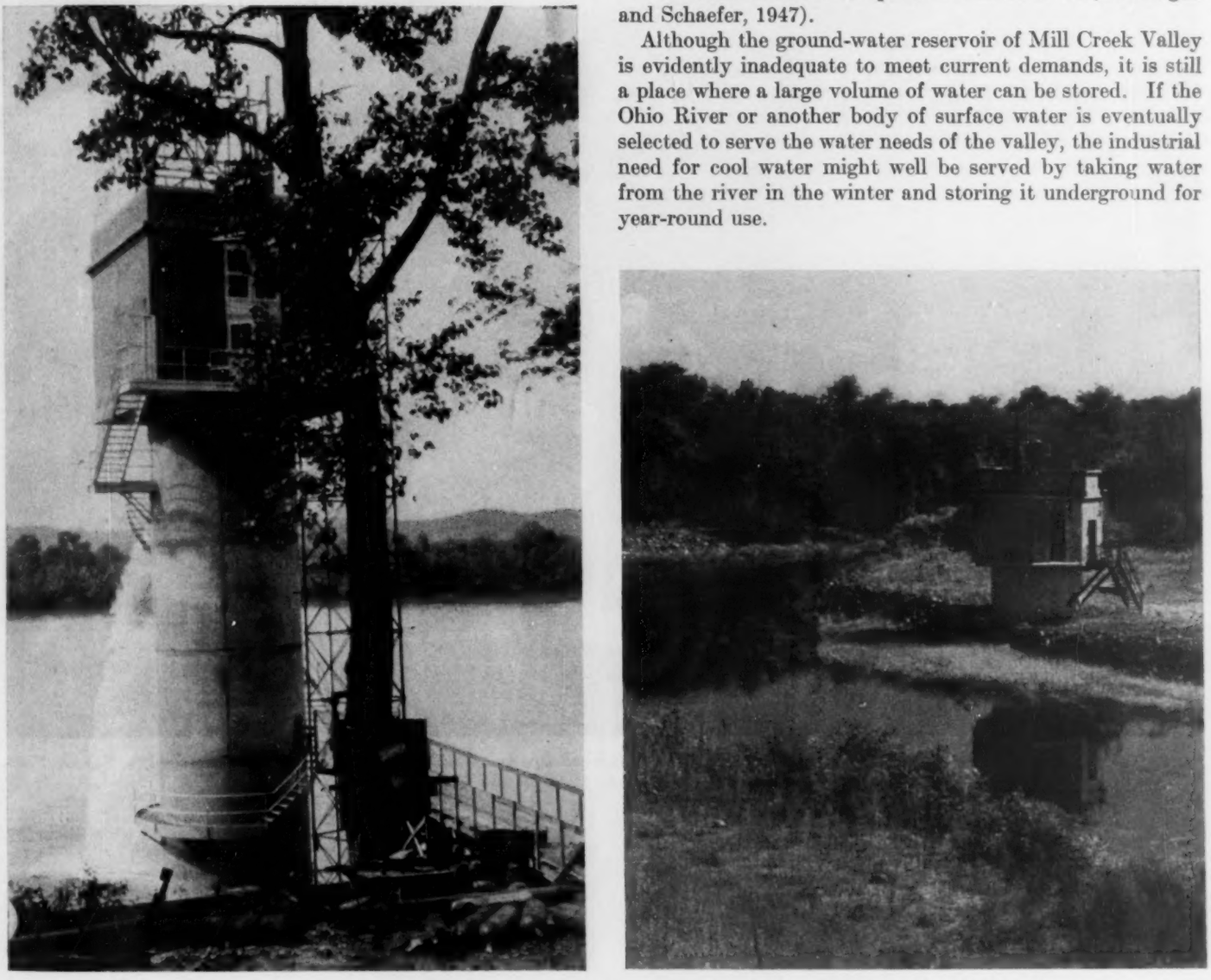

FIGURE 33.—*Collector wells dependent upon river infiltration. (Left) Well of the National Carbide Co., along the south bank of the Ohio River at Louisville, Ky., yields 4 million gallons a day. The pumped water is replaced by infiltration from the river. (Right) The American Cyanamid Co.'s well at Wallingford, Conn., is 80 feet deep, and has more than 1,000 feet of lateral pipe. The well yields 5 million gallons a day.*

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FIGURE 34.—*Flooding basins for artificial recharge at Des Moines, Iowa. Muncipal supplies are obtained from an infiltration gallery along the Raccoon River, in background. (Photo by courtesy of D. L. Maffitt, Des Moines Water Works.)*

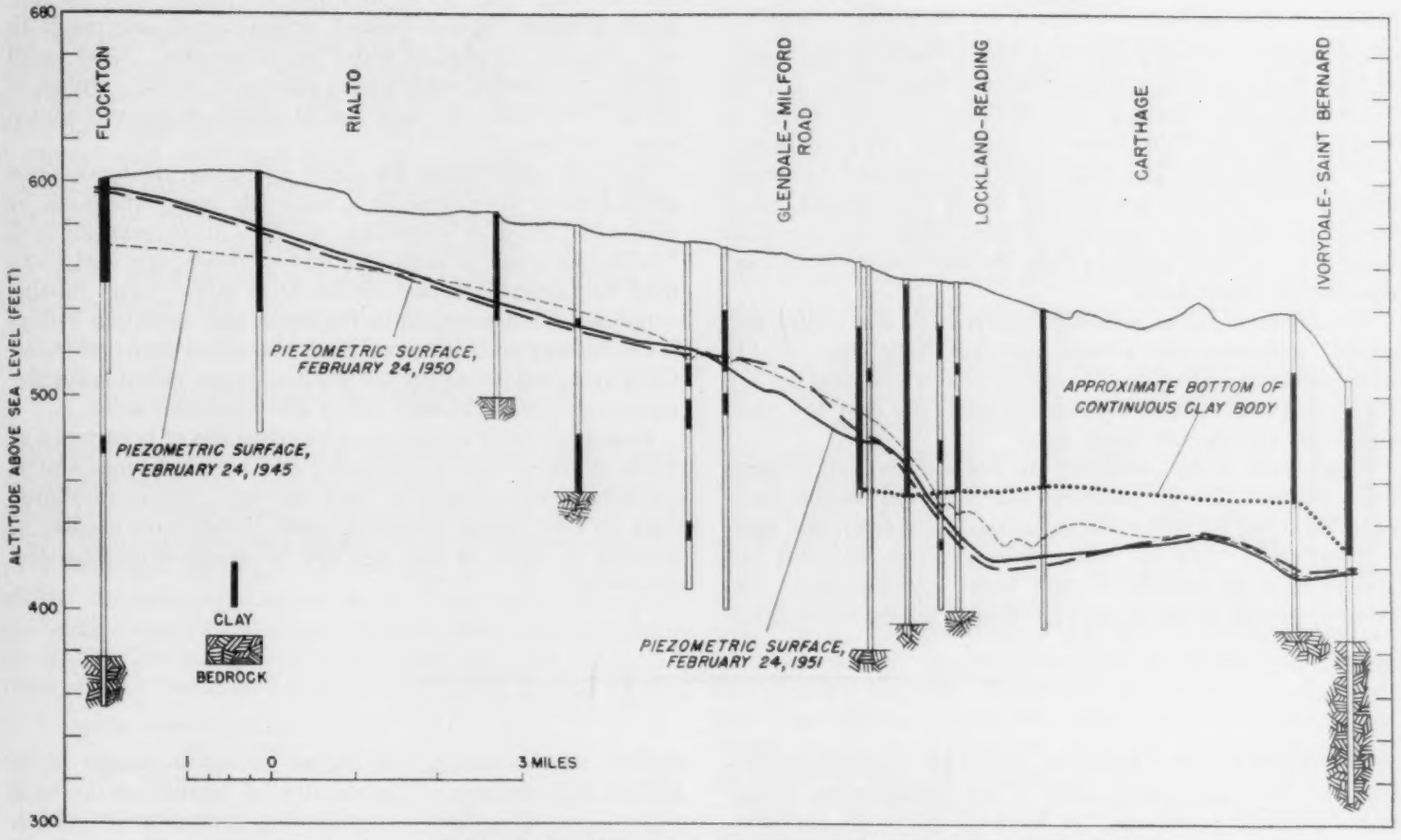

FIGURE 35.—*Section of Mill Creek Valley, Butler and Hamilton Counties, from Flockton south to Ivorydale, Ohio.*

Unglaciated Appalachian Region

Summary

THIS REGION includes the unglaciated parts of the Appalachian Valley and Ridge province, the Blue Ridge, and the Piedmont, from Georgia and Alabama on the south to Pennsylvania and New Jersey on the north. It is characterized by mountains and hilly uplands separated by broad valleys. The rocks are mainly dense but include some cavernous limestones, and all the hard rocks are somewhat broken by crevices resulting from the earth movements that created the mountains.

The region is one of generally high rainfall and runoff, and rather well-sustained stream flow resulting from evenly distributed precipitation. Large ground-water supplies are rare, but small, reliable supplies are generally easy to obtain except on hill and mountain tops.

Here again, water problems are less serious than in some other regions. In this populous and important region, however, the need for water for industrial, municipal, and agricultural supply and for power is very great, and it is not always easy to develop enough water economically. Soil erosion, stream pollution, and flooding of settled valley lands are problems that can be met only by proper land use and more adequate stream control, which would also result in more regular supplies of water for other uses. Most small cities have trouble maintaining adequate public supplies of water from wells, yet they can ill afford expensive surface-water systems.

There is opportunity for many additional moderate-scale ground-water developments in favorable areas, which can be discovered only by systematic study. More scientific well location in areas of limestone and of dense, creviced rocks may be expected to pay dividends in larger, more reliable supplies. Thin alluvium in Piedmont and mountain valleys is a promising and hitherto almost untouched source of water. Conditions are promising for small-scale yet valuable supplemental irrigation in many valley and Piedmont areas.

Relatively little is known as to principles of occurrence of water in limestones of the valley and ridge province and in the dense creviced rocks of the Piedmont. Many additional data on flow characteristics of small streams are needed, in relation to effect of land use and to design of bridges and reservoirs.

This region includes the Blue Ridge physiographic province and the unglaciated parts of the Appalachian Valley and Piedmont provinces. It includes parts of Alabama, Georgia, Tennessee, South and North Carolina, Virginia and West Virginia, Maryland, Delaware, Pennsylvania, and New Jersey. Part of the region is in the Mississippi River Basin and is drained by the Tennessee and Ohio Rivers, but most of it is drained by Atlantic and Gulf coastal streams. The region as outlined in figure 36 includes Meinzer's Blue Ridge-Appalachian Valley and Piedmont ground-water provinces.

The region is a highland area surrounded by the central and coastal lowlands of the continent. It includes mountain ranges, steep ridges, broad valleys, foothills, and an extensive belt of rolling land. In general these highlands have a colder climate than the adjacent lowlands. The region is humid and includes the areas of heaviest annual precipitation in the eastern United States.

Comparison With Western Mountain Ranges

The Appalachian region, whether glaciated or not, has several features in common with the western mountain-range region. Each includes the highest mountain ranges in its half of the country. The density of population in each region is less than that in surrounding lowland areas. Both regions receive more precipitation and are colder, latitude for latitude, than the adjacent lowlands. And of course, because of their high altitudes and heavy precipitation, the regions are the headwaters for many important streams in the East and in the West.

But the Appalachian region is not nearly so high; and, although it may receive considerable precipitation in the form of snow, it does not hold it until late spring or early summer. The growing season is longer, and the valleys and moderate slopes, and even some fairly steep slopes, have been cleared and cultivated for generations. Throughout the growing season the lowlands receive enough precipitation so that irrigation is not essential, although agricultural production could be increased substantially by provision for a constant supply during the growing season, when occasional droughts reduce crops to half or a third of normal. There is not yet an urgent demand for the water flowing from the Appalachians, as far as agriculture is concerned, but that water is important for power and for cities and industrial users.

In the Appalachian region, as in the western ranges, the

dominant bedrocks are crystalline or metamorphic, or well-consolidated sedimentary rocks. In the unglaciated Appalachian region, these rocks provide the only ground-water reservoirs in most of the area, either in the joints and other fractures that occur in the fresh rock to considerable depth or in the loose and weathered surficial materials that are formed from those rocks. This is analogous to the occurrence of ground water in the western ranges. Also, as in the western ranges, there are some limestones in the unglaciated Appalachian region, some of which contain large and extensive solution cavities and channels that facilitate the storage and movement of ground water.

Gravel and sand beds have been deposited in stream valleys, and some may have sufficient volume to yield large quantities of water to wells. These watercourses may well be the best potential sources of large supplies for wells in the region, but there has been relatively little exploration or development to date.

The Crystalline and Metamorphic Rocks

Crystalline rocks, including chiefly granite, gneiss, and schist, are important sources of water in the Piedmont, which is the well-populated belt of rolling land east of the Blue Ridge. These rocks furnish water of excellent quality to innumerable wells and springs that provide practically all the domestic supplies and many of the small industrial and public supplies (the largest supplies being obtained from streams). The springs are usually small and may dry up in some seasons, because they are mostly from the weathered surficial rocks. The wells are of two types: shallow-dug wells with large infiltration surfaces, receiving the seepage from weathered surficial material, and deeper-drilled wells that obtain some supplies from water-bearing fractures.

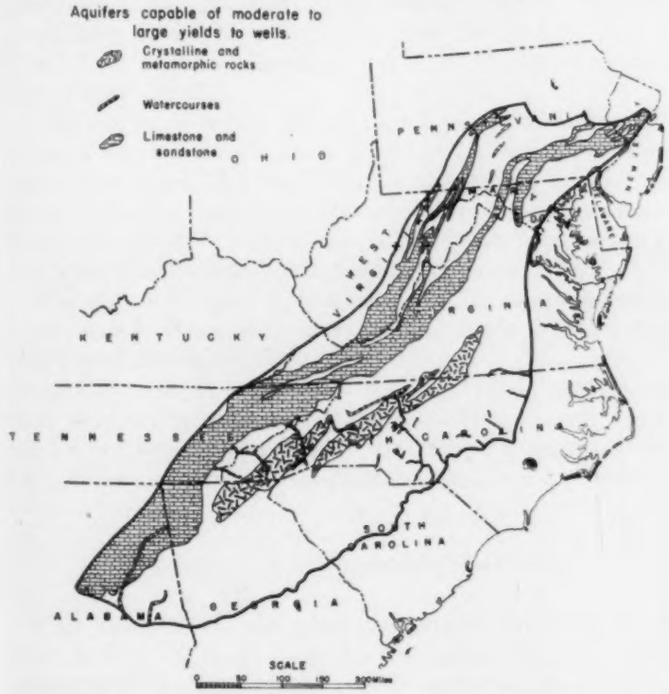

FIGURE 36.—*Unglaciated Appalachian region: saturated crystalline rocks of low storage capacity, limestone and sandstone, and some watercourses.*

Granitic rocks commonly have the property known as sheet structure, which produces parting planes that are usually more or less parallel to the rock surface on hills and in valleys. These control the circulation of subsurface water, and the openings under the valleys are the receptacles for much subsurface water that percolates along these planes from nearby upland slopes. Wells drilled in lowlands in sheeted granitic terranes almost invariably produce greater quantities of water than those on the uplands; in some places such wells are capable of supplying 50 to 200 gallons per minute. Generally in granites, as well as other crystalline rocks, pore space is most abundant near the surface, and few wells obtain much water at depths greater than a few hundred feet. The water from granitic rocks is usually of excellent quality.

In the vicinity of Atlanta, Ga., the predominant rocks are gneiss, schist, and granite, and the greatest quantities of water are obtained from the gneissic rocks. Municipal and industrial supplies are obtained from drilled wells, and a well yielding more than 60 gallons per minute is considered an excellent producer. The least mineralized water is obtained from granitic rocks. Rural supplies are obtained chiefly from residual material overlying the bedrock, by means of dug wells that generally yield less than 5 gallons per minute. Gneiss is one of the best producers of water in other parts of the Piedmont, too, particularly in North and South Carolina. Schist also yields some water, but it is generally one of the least permeable of the crystalline rocks, and in some places it forms the confining rock that gives rise to artesian pressure in wells.

West of the Piedmont, rocks have been intensely folded to form the Blue Ridge and the valleys and ridges farther west. The metamorphic and sedimentary rocks of this area carry water chiefly in fractures. Some wells have developed water supplies from quartzites, coal, and even from slate. Sandstones are important aquifers, particularly in the northeast part of the region, in New Jersey and eastern Pennsylvania. Many wells in sandstone produce industrial or domestic supplies in Newark, other north Jersey towns, and in the north suburbs of Philadelphia.

The limestones and dolomites, however, are among the best aquifers in this mountain region. The Shenandoah Valley in Virginia is a broad, trenchlike valley excavated mainly in limestone, and the valley is famed for its numerous caverns. In this valley, as in the Ozark region in Missouri, features are largely those of underground drainage, rather than of large underground storage of water. There are numerous sinks, copious springs in the deep valleys, and a general absence of brooks tributary to the larger streams, all indicative that the runoff from large tracts moves through underground channels until it reaches the deep valleys.

The quantity of water in storage in the limestone is unknown but is presumed to be large, because the flow of

streams is well-sustained in dry periods. Wells obtain moderate to large supplies of water from limestone reservoirs in a few places. As an example, more than 20 million gallons a day is pumped from wells at Waynesboro, Va., for manufacture of paper and pulp, and rayon.

For the region as a whole, however, the possibilities of water supply from the limestones have not been explored sufficiently to show how large the ground-water reservoirs may be, or where the conditions are most suitable for wells. Undoubtedly there are some places where wells could obtain large supplies, with adequate replenishment from infiltration and from underground channels. In these places, wells would have a sustained perennial yield, and might also be effective in reducing the peak outflow of streams, thus effectlng some regulation of stream discharge.

Except for the limestones, the consolidated rocks of the region probably have too little porosity (and therefore too little capability for storage) to be effective regulators of stream flow. The conditions at the Coweeta Experimental Forest may be representative (U. S. Forest Service, 1948). This forest is on rugged terrain in western North Carolina. The forest soil has an average thickness of about 4 feet, with soft disintegrated gneiss below. The soil contains much humus and is exceedingly porous, and absorbs all the water from precipitation, which ranges from 65 to 90 inches in an average year. But it is so thin that it provides only detention storage of water, and much of the water from storms reaches the streams within a few hours or days. The underlying disintegrated rock and the fractures in the fresh rock retain the water for a longer period, and are the sources of perennial springs and of dry-weather stream flow. But they cannot take a very large part of the water that infiltrates into the soil.

Potentialities of Watercourses

Except in the limestone areas, the consolidated rocks of the unglaciated Appalachian region are poor places to drill wells, if yields of several hundred gallons per minute are desired. For large quantities of ground water the best prospects are probably gravel and sand beds in the alluvium of perennial streams. The potentialities of watercourses have been very little explored, but gravel accumulations are to be expected in favorable places along many of the streams, particularly in the steeper terranes, and it is certain that many watercourses contain gravels and sands that could furnish large water supplies to wells. Reconnaissance studies are the basis for the mapping of several valleys in North Carolina (see fig. 36) as potential sources of substantial ground-water supplies, even though the stream deposits are generally rather thin. Similar studies have not been made in other States that are included in the unglaciated Appalachian region.

Glaciated Appalachian Region

Summary

THIS REGION includes the glaciated part of the Appalachian Mountains and all of New England. It is characterized by hilly or mountainous terrain, with thin glacial drift on the uplands and thicker drift in the valleys.

The region is one of relatively abundant supplies of water of good quality. Precipitation is moderately high and the climate is cooler than that of the region to the south, so that evapotranspiration is less and the runoff is proportionately high. Ground-water supplies are small in the uplands but large in many of the valleys. They are especially large, and as yet relatively untouched, in many New England valleys.

Stream pollution is a serious problem but is under vigorous attack. Soil erosion is less of a problem than in the region to the south. There are some local shortages of water that are economic rather than hydrologic, but are nonetheless important. New York and metropolitan New Jersey are especially in need of additional large-scale water developments, and these are being planned. There are a few problems of local overdevelopment of ground water, all under more or less vigorous attack.

Much additional ground-water development is feasible in the glaciated valleys, even in some areas only a short distance from centers of heavy withdrawal. New England, where surface supplies have been relied on for most large-scale uses, is most promising and ground-water use is increasing.

The principal need is for systematic study to locate areas of productive glacial aquifers and to evaluate the supplies in areas of pumping in terms of safe sustained yields. Adequate studies have been made in only a few communities, and ground water, one of the principal underdeveloped resources of the region, is still little known.

This region is a northward continuation of the eastern highlands, and differs from the unglaciated Appalachian region only in that it has been covered by continental glaciers. The glaciated Appalachian region includes practically all of New England, plus the eastern part of New York and the northern parts of Pennsylvania and New Jersey (fig. 32).

This glaciated region includes some of the highest mountains of eastern North America, as well as lower summer-resort mountains like the Catskills and Adirondacks. The region is humid and relatively cold and give rise to many perennial streams. Most of these drain to the Atlantic Ocean but a few find their way into the St. Lawrence River.

The region is fairly homogeneous as far as ground-water occurrence is concerned, corresponding to the Northeastern Drift ground-water province of Meinzer. The region is essentially one in which the drainage modifications and drift deposition typical of the glaciated Central region have been superimposed upon the rugged topography and hard rocks typical of the unglaciated Appalachian region.

Variety of Water-Storage Facilities

The bedrocks of the glaciated Appalachian region are very similar in their water-bearing properties and yields to those of the unglaciated region to the south. Most of New England is underlain by metamorphosed sediments, which yield small quantities of water to wells chiefly from joints and fractures. Drilled wells obtain domestic and small industrial supplies from these fractures. In the Greater Boston area the aggregate pumpage of water from hundreds of "rock" wells runs to millions of gallons a day, and doubtless the metamorphic rocks in other areas would be similarly productive with such development.

Sandstones are important aquifers in some parts of the region, notably in northern New Jersey and in the Connecticut River Valley in Connecticut and Massachusetts. They yield a moderate quantity and good quality of water to many wells in these heavily industrialized areas.

Most of the natural facilities for storage of water in this region are formed by the glacial drift rather than by the underlying bedrocks, which as a rule are relatively impervious. Surface storage is provided in numerous depressions, most of which are occupied by lakes. The glacial drift also provides the most productive ground-water reservoirs of the region. Gravel and sand lenses in glacial till provide small quantities of water for many domestic wells.

The chief water bearers of New England, however, are the glacial outwash deposits. These deposits are of considerable extent along the coasts of Maine and Massachusetts, in the Connecticut River Valley, and in several other places in New England. In many places the gravels and sands are permeable enough to yield large supplies to wells.

Several cities in New England obtain their water from outwash plains or from other permeable glacial deposits.

Thus Portsmouth, N. H., takes 1½ million gallons a day from morainic deposits; Framingham, Mass., and Dover, N. H., have wells in gravel and sand near lakes of glacial origin. In New York, Albany obtains most of its municipal water supplies from a surface reservoir about 20 miles south of the city, but wells in glacial deposits within the city limits yield a supplemental supply of about 3 million gallons per day.

Watercourses and Abandoned or Buried Valleys

The lowlands of this rugged region are the areas in which population is concentrated, and are therefore the areas of prime importance to man. During the Ice Age these same areas were the sites where the ice sheets were thickest, and as the ice melted many of the valleys became the channels that carried away the water. Now those valleys contain some of the thickest and most permeable glaciofluviatile deposits, and therefore some of the most productive (or potentially most productive) ground-water reservoirs of the region.

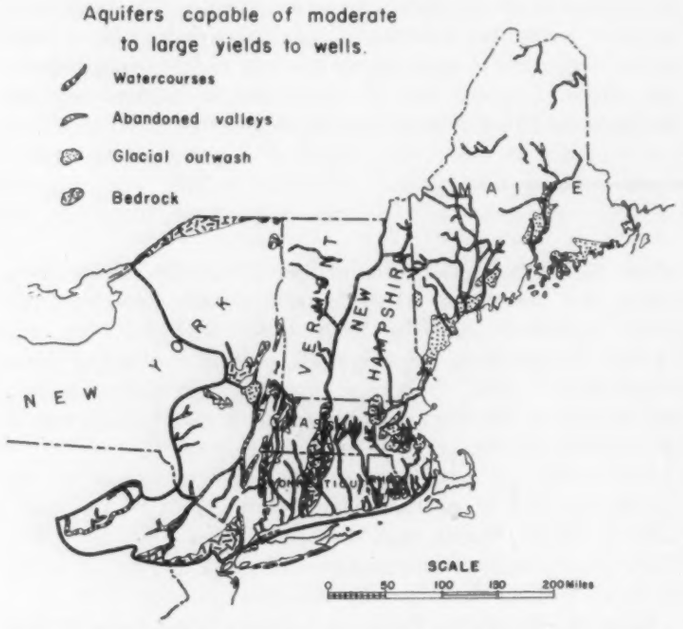

FIGURE 37.—*Glaciated Appalachian region: storage facilities chiefly of glacial origin, including watercourses and glacial drift.*

Many of the valleys that carried away the glacial waters are now occupied by perennial streams. The ground-water reservoirs in these watercourses have the same advantages as those in other watercourses throughout the Nation for unless they are insulated from the river, water pumped from them can be replenished by river infiltration.

Many cities in New England depend upon wells along watercourses for municipal supplies. Naugatuck, Conn., obtains nearly 5 million gallons a day from a well in gravel along the Naugatuck River. Lowell, Mass., uses more than 800 wells in gravel beds along the Merrimack River to supply nearly 6 million gallons a day, and Concord and Nashua in New Hampshire also obtain their municipal supplies from wells along that watercourse.

Relatively heavy ground-water development has been made in Massachusetts along the watercourse of the Charles River, which drains into Boston Bay and has a small drainage basin that is almost entirely within commuting distance of Boston. The cities of Brookline, Dedham, Newton, and Waltham, with a combined population of about 175,000, draw more than 16 million gallons a day from about 600 small wells in gravel near that river, and several other towns in the metropolitan area obtain their supplies from wells along brooks tributary to the Charles.

On the other hand, many of the principal watercourses of New England have not even been explored for their ground-water potentialities. It is likely that permeable gravels are abundant in many places in the St. John, Penobscot, Kennebec, Androscoggin, Connecticut, and Housatonic River systems, to mention several of the largest.

Abandoned or buried valleys of Ice Age streams are numerous in the region; several have been mapped in Maine and in Massachusetts (fig. 37). New Britain, Conn., is along one of the abandoned valleys of the glacial Connecticut River, and near the present divide between South Brook and the Mattabesset River. The city pumps about 8 million gallons a day from 90 wells drilled into the sand and gravel along canals connecting these north- and south-flowing streams. Cambridge, Mass., also obtains its water supplies from glacial sands in a buried valley.

Atlantic and Gulf Coastal Plain

Summary

THIS REGION extends from Long Island and the sandy islands and capes of Massachusetts clear to Texas, and includes the Mississippi Embayment as far north as Cairo, Ill. It is characterized by seaward-dipping strata, mostly unconsolidated, of sand, clay, marl, and limestone, overlying older rocks such as are exposed in the Piedmont. Except in its extreme western part in Texas, the region has a humid climate.

The Coastal Plain is probably the region most abundantly endowed with water of all those in the United States. Both the humid climate and the unconsolidated nature of the strata and presence of many permeable sand and limestone beds lead to high infiltration, generally well-sustained stream flow, and availability of prolific aquifers at one or more levels beneath nearly every site. The region is the only one where a substantial part of the infiltration passes beneath the coast rather than returning to the streams, so that the use of that part of the ground water does not deplete stream flow. This quantity, though only a small fraction of the total infiltration, is large in an absolute sense.

Though characterized by numerous productive aquifers, the region is susceptible to salt-water encroachment in coastal areas. In the Miami, Fla., area the aquifer is one of the most productive ever investigated by the Geological Survey, yet a salt-water problem developed through improper drainage practices is on the way to being solved only because the area was subjected to one of the most intensive hydrologic studies yet made. In some areas, particularly parts of the coast of Texas, but in many other places as well, only brackish or salty ground water is present; in others, there may be only one fresh-water aquifer whose supply is not adequate to meet the local needs. In a few areas, including sizable ones in Texas, Louisiana, and Mississippi, only non-water-bearing sediments are present within feasible drilling depths. In some important rice-growing areas the same tight subsurface material that permits flooding the rice is responsible for lack of local recharge, and ground-water storage is being depleted by pumping.

The possibilities for additional ground-water development are very great, in spite of local overdevelopment. By means of proper location of future developments and redistribution of pumping in areas of present heavy pumping, an enormous amount of ground water can be withdrawn. There are excellent possibilities of making ground-water developments in places that would provide both needed water supplies and storage space in aquifers that would take the peaks off flood flows in the streams. Also, there are possibilities for use of Coastal Plain formations for storage of natural gas and other petroleum products in a way that would do no harm to fresh water, yet, at low cost, would increase the security of eastern communities dependent on these fuels.

The occurrence of usable aquifers and the amounts of water safely available from them are still only imperfectly known, even in States such as Texas where studies have been on a substantial scale for more than 20 years. Obviously the great promise of the Coastal Plain's ground water can be realized only if adequate information about it is gathered. The hydraulics of aquifers in reference to storage of petroleum products is almost *terra incognita*. Much additional study is needed to find safe methods of ground-water development in coastal areas where salt-water encroachment is a possibility. Study of occurrence and recovery of shallow ground water in the Florida Keys and similar areas is needed. Use of pressure-relief wells along the Mississippi, to avoid sand boils and failure of levees, is another promising field of study

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The Coastal Plain ground-water region extends from the Rio Grande eastward along the Gulf coast and northward along the Atlantic coast, and also forms a broad arm in the Mississippi River Valley as far north as the southern tip of Illinois (fig. 38). The region is bordered on the north by the Unglaciated Central region, and farther east by the Unglaciated and Glaciated Appalachian regions. It corresponds to Meinzer's Atlantic Coastal Plain ground-water province, except that it includes Long Island and the Cape Cod Peninsula at its eastern end, and does not include the Edwards Plateau in Texas.

The Coastal Plain is a ground-water region of great importance. Its wells yield more than 15 percent of all the water produced by wells in the United States. Thus the region ranks second to the Arid Basin region in developed ground-water supplies.

The Coastal Plain rises gradually from the coast, and its highest areas are only a few hundred feet above sea level. The gentle seaward slope of the plain is comparable to that of the Continental Shelf, which extends from the coast line on out to the sea. Northward from North Carolina the Coastal Plain has a progressively diminishing land area,

especially where Chesapeake Bay and Delaware Bay encroach upon it. Still farther north the coast line and the submerged Continental Shelf come right up against the flank of the Appalachian region, and the Coastal Plain exists only as islands or peninsular remnants such as Long Island, Marthas Vineyard, and Cape Cod.

The western tip of the Coastal Plain receives somewhat less annual precipitation than the national average of 30 inches. In the rest of the region, however, the precipitation is well above, and in parts of Mississippi, Alabama, and Florida it is more than twice the national average. In the region as a whole, precipitation is more abundant than in any other of the 10 regions described. The climate of the region ranges from subtropical in southern Florida to intemperate in New York. Much of the soil is fertile, and the Coastal Plain thus includes some of the best agricultural lands in the country.

Salinity Relationships

One of the advantages of living in the Coastal Plain region is nearness to the ocean. The ocean has been an important element in the geologic history of the region, for most of the sediments have been deposited either in salt water or in coastal areas just above sea level. Much of the Coastal Plain is now the border zone where the fresh water of the continent meets the brine of the ocean, and all of it at some time in its history has been within that zone. It is not surprising, therefore, to find that the present coast line does not by any means represent a dividing line between fresh and salty ground waters.

Fresh water could be obtained in the middle of Chesapeake Bay by drilling a well into the sand aquifers under the floor of the bay. The barrier beaches on the south shore of Long Island, and along the Jersey coast at Atlantic City

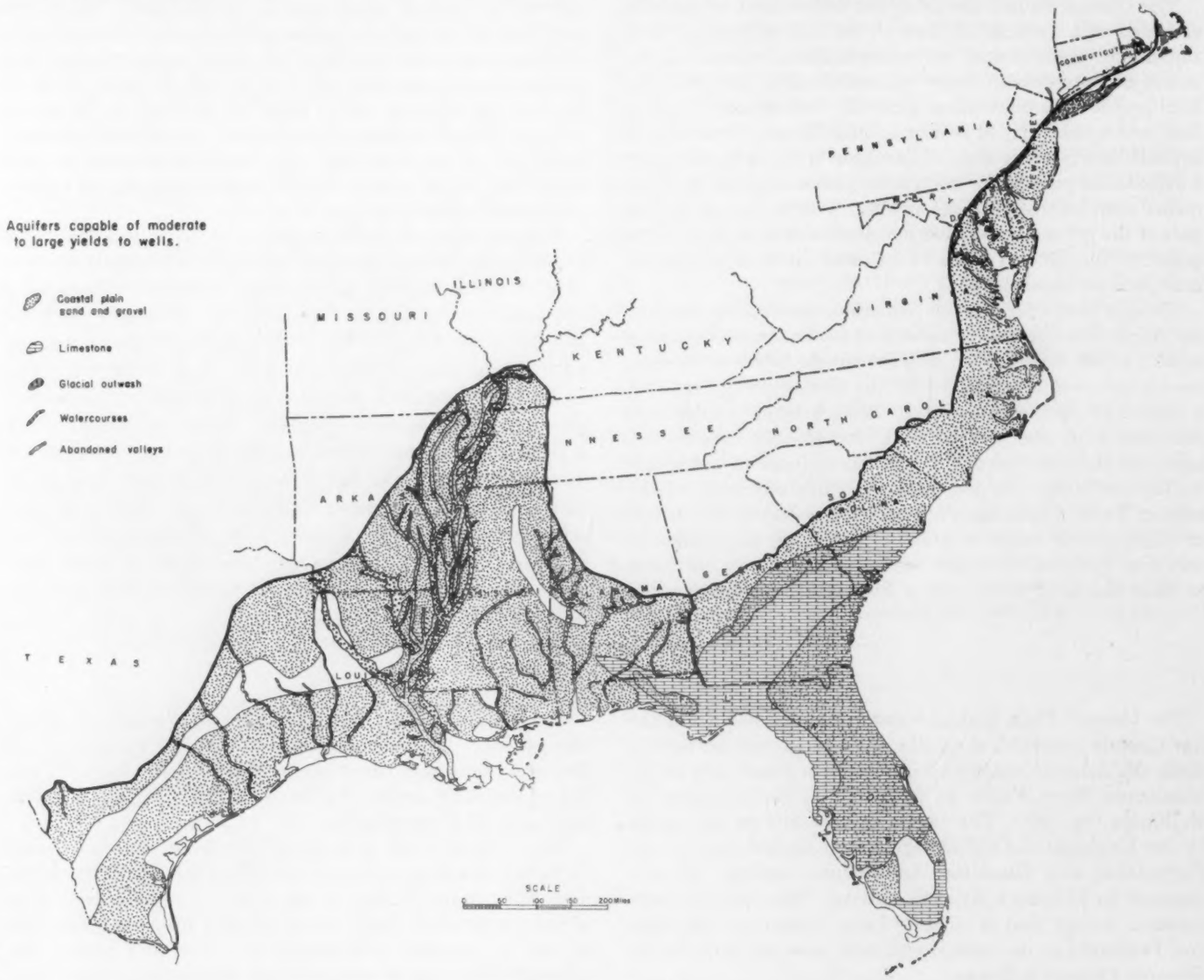

FIGURE 38.—*Coastal Plains: chiefly coastal sediments with problems of salinity; important aquifers of limestone and glacial outwash in places.*

and many places farther south, are almost entirely separated from the mainland by salt water; yet fresh water is obtained from deep wells. And Mississippi has islands (Cat Island and Horn Island, for instance) as much as 10 miles offshore where flowing wells yield fresh water that once fell as rain upon the mainland.

On the other hand, there are many places within the land area of the Coastal Plain where wells produce saline water, and that is not so good. In some places, as for instance in parts of tidewater Virginia and in the deeply buried limestones under the Everglades in Florida, it appears that the water in the aquifer has always been saline or brackish, probably because the sea water that once filled them has never been flushed out completely.

At many other places wells that originally produced fresh water now yield brackish or saline water. These are the areas of salt-water encroachment, where man has caused some deterioration in quality of water in ground-water reservoirs. In most places salt-water encroachment has been caused by pumping and thus lowering water levels to the extent that saline water is induced to flow toward the well. However, salt water has entered some aquifers after protective covering has been removed in dredging operations, or after the water table has been lowered by drainage canals.

Problems of salinity in water from wells have developed at places in nearly every State that extends into the Coastal Plain, and such problems are more common in the Coastal Plain than in any other ground-water region in the country. Instances of salt-water encroachment can be cited for each of the types of aquifers discussed in the following sections. Thus salt water has moved in to replace the fresh water in glacial deposits at Provincetown, Mass., near the northern tip of Cape Cod, and also in Brooklyn, N. Y., at the west end of Long Island. It has entered wells that were recharged by infiltration from tidal streams at Wilmington, N. C., and at Mobile, Ala. Salt water has moved into limestone in about one-fourth of the peninsula upon which St. Petersburg, Fla., is located. And fresh-water supplies in coastal sand and gravel beds have been contaminated by salt water at many places, among which might be mentioned Texas City, Tex., Pensacola and Fort Myers, Fla., and Atlantic City, N. J.

FIGURE 39.—*Pumping for irrigation of rice near Mermentau, La.*

Sand and Gravel of the Coastal Plain

Most of the Coastal Plain is underlain by a thick succession of loose or semiconsolidated sediments in beds that dip gently seaward. In this succession there are many beds of sand and some of gravel. Interbedded with these aquifers are less permeable materials which act as confining layers, with the result that many aquifers contain water under artesian pressure, and flowing wells are common in the lower areas.

The most heavily developed sand and gravel aquifers in the Coastal Plain are in the rice-growing areas of eastern Arkansas, southwestern Louisiana, and southeastern Texas. The annual pumpage for rice irrigation in those areas approaches 2,000,000 acre-feet, which is nearly half of all the water pumped from wells in the Coastal Plain (fig. 39).

Rice growing takes a lot of water, for the fields are flooded when the plants are 6 or 8 inches high, and standing water is maintained almost continuously for 2 or 3 months, until the crop is nearly mature. Soils in rice fields must be impervious enough to inhibit downward percolation of water, and inevitably therefore the underlying ground-water reservoir must receive its replenishment by lateral movement from recharge areas that may be several miles away.

The aquifers that have been developed for rice irrigation hold vast quantities of water, but the combination of heavy pumping and distant sources of replenishment has caused the storage to be seriously depleted in some areas. In the Grand Prairie of Arkansas (between the White and Arkansas Rivers) where rice has been irrigated from wells for more than 40 years, the storage of water in the aquifer has probably been reduced by about 2,000,000 acre-feet, which is eight times the quantity pumped from wells in 1949 (Engler and others, 1945). In southwest Louisiana the water level has been lowered at an average rate of half a foot a year for the past 40 years, and in September 1949 it was below sea level under an area of about 4,000 square miles (Jones and Turcan, 1949). The aquifer is more than 900 feet thick in some places, but in those places saline water occupies the lower 200 feet of the formation. In the areas of most concentrated draft the salinity of pumped water is gradually increasing, perhaps because of water rising from the lower part of the aquifer.

The Houston-Galveston area is another area of intensive pumping from sand and gravel of the Coastal Plain (Lang and Winslow, 1950). Houston is the largest city in the Nation dependent upon ground water for all municipal and most industrial supplies, and the metropolitan area is comparable to the Los Angeles metropolitan area in annual pumpage from wells. This concentrated draft has been partly at the expense of storage: since 1940, water levels in wells have declined more than 70 feet in downtown Houston, and more than 100 feet in the Pasadena industrial

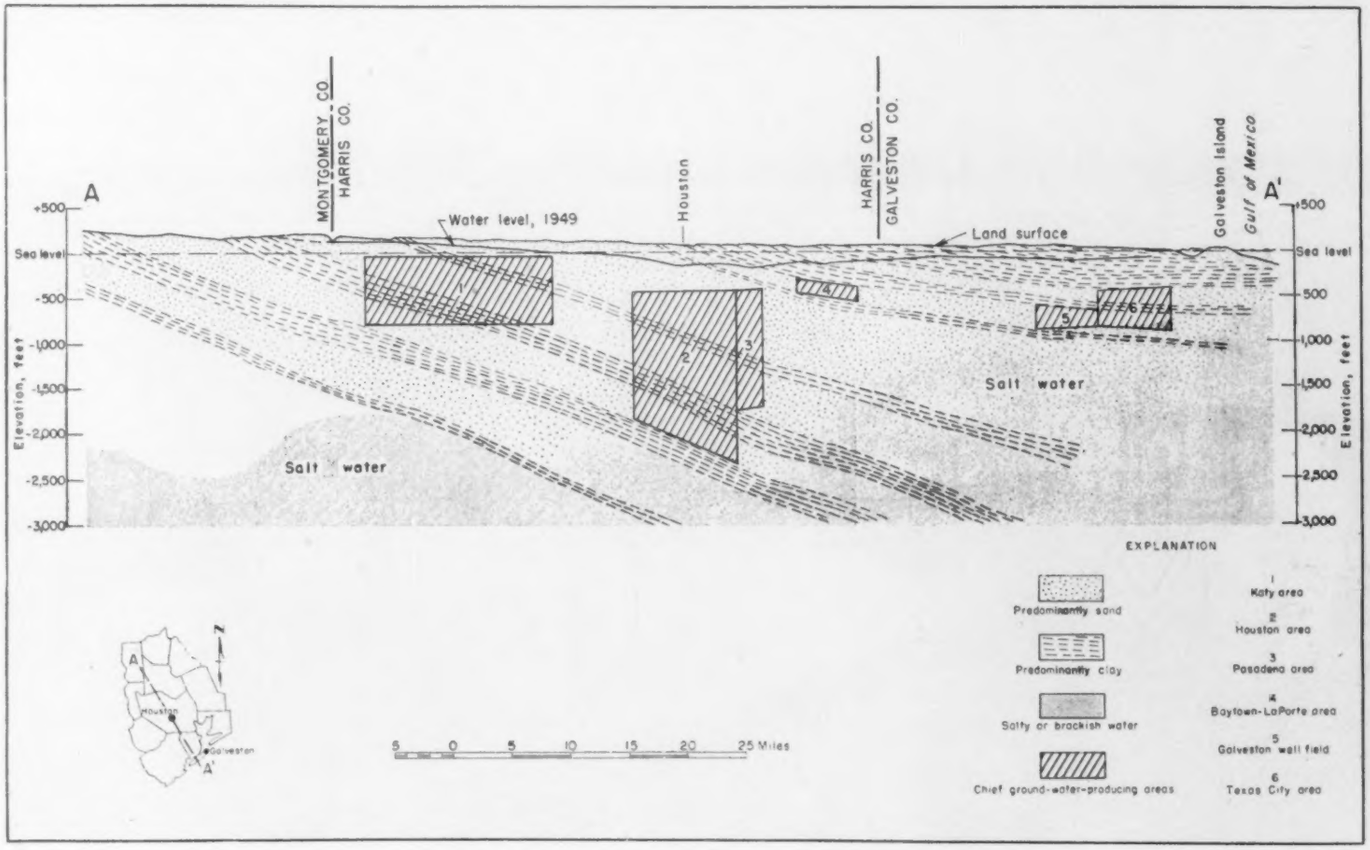

FIGURE 40.—*Water-bearing formations in the Houston region.*

area to the east. There is still much water in the ground-water reservoir, for fresh water can be obtained from depths as great as 2,500 feet in Houston. The city is 50 miles from the Gulf of Mexico (though connected with it by Galveston Bay and the Houston Ship Canal), and there has not yet been any indication of salt-water encroachment into its wells. Galveston and Texas City, however, are both close to salt water, and both have been troubled by increases in salinity of water from pumped wells (Galveston's wells are on the mainland, for the island itself has no substantial quantity of fresh water) (figs. 3, 40, and 41).

Baltimore, Md., obtains its municipal supply from surface water, but water is pumped from wells for industrial use at an average rate of about 40 million gallons a day. Few wells are now pumping water that is entirely free of contamination, although most of the water pumped is only slightly contaminated. The Baltimore Harbor lies over part of the recharge area for a deep artesian aquifer, and pumping has induced infiltration of sea water until the water now pumped from wells in the harbor area is about as saline as that in the harbor. Continued pumping removes some of this salt water and prevents it from moving into well fields farther east which are not yet seriously contaminated. A shallow aquifer is also overlain by salt water along the Patapsco estuary, and this salt water has moved in as water levels have been pulled down below sea level by pumping. This shallow aquifer is also contaminated by sulfuric acid and copper sulfate from acid and metal-refining plants that have been situated in the area at one time or another during the past century.

These are only a few of the numerous areas along the Coastal Plain where large quantities of water are obtained from sand and gravel aquifers. Several other areas have had difficulties with salt-water encroachment, but those areas are small pinpoints of concentrated draft in comparison with the total area of the Coastal Plain. In the region as a whole large quantities of ground water remain still unused and awaiting development, and will discharge to the ocean until some use is made of the water. According to a reconnaissance in North Carolina, for instance, aquifers of the Coastal Plain in that State could yield water in quantities at least 10 times greater than that yielded by all existing wells.

FIGURE 41.—*Houston municipal well, 2,365 feet deep.*

Limestone in the Southeast

The limestones of Florida and southeast Georgia are some of the most permeable aquifers known to man (fig. 43). The yield of wells tapping these limestones, including many large flowing wells, is of the order of 600 million gallons a day. Silver Spring in Florida is the largest limestone spring in the country, for it has an average discharge of more than 800 cubic feet per second, or more than 500 million gallons per day (figs. 42, 44, 45).

Savannah, Ga. (Warren, 1944), obtains about 50 million gallons a day by pumping from permeable limestone 750 feet thick, whose top is about 200 feet below sea level. Prior to 1880 the artesian pressure was sufficient so that wells in Savannah flowed, but pumping has lowered the artesian pressure as much as 100 feet, and water levels in some wells are now more than 50 feet below sea level. The effect of pumping extends more than 20 miles in all directions. The water in the limestone is somewhat saline in an area 30 miles northeast of Savannah, and observations are being made periodically at wells in the intervening area, in order to detect increasing salinity in ample time for remedial action. The water in the Savannah River is being developed to meet the city's increasing requirements.

The limestones of Florida under natural conditions carry

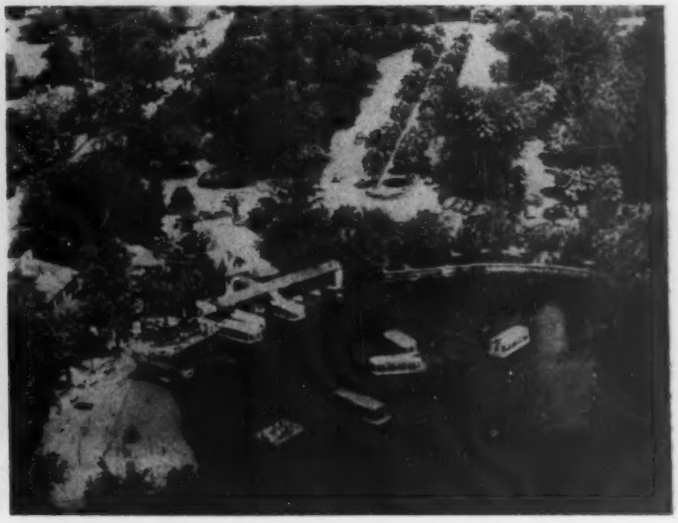

FIGURE 42.—*Silver Spring, Fla., the country's largest limestone spring.*

large quantities of fresh water to sea. Efforts to hasten this transit by constructing drainage canals have backfired in some coastal areas, notably at Miami, where salt water has moved up the canals and into erstwhile fresh-water bearing limestones. In some places, also, concentrated draft has induced inflow of saline water into aquifers (fig. 46).

Glacial Deposits in the Northeast

Continental glaciation has extended into parts of the Coastal Plain, as in the Appalachian and central regions. However, the glaciated area, including only Long Island, Cape Cod, and a few near-shore islands, is too small to justify subdivision of the region into glaciated and unglaciated components.

Long Island is the major ground-water reservoir of the glaciated part of the Coastal Plain region. Some water is obtained from sand beds similar to those that underlie the Coastal Plain farther south, but by far the most important water bearers of Long Island are the glacial outwash deposits. All the ground water comes from precipitation on the island, and recharge is estimated to be at an average rate greater than 1 billion gallons a day, of which more than two-thirds is eventually discharged unused into the ocean.

Brooklyn, at the western tip of Long Island, has had serious problems of salt-water contamination in wells. Although this cannot be called a shortage in the *midst* of plenty, because of geography, it is nevertheless true that Brooklyn has run into difficulties in obtaining water from one end of an island-wide and exceptionally productive ground-water reservoir. In Brooklyn the island is only 6 to 8 miles wide between East River and Jamaica Bay, both of which are saline. In 1903 the water table was as much as 20 feet above sea level, but by 1932 it had been lowered by pumping to positions as much as 15 feet below sea level, and salt water had moved in from both east and west. Water levels in wells continued to decline gradually until 1941, when they were below sea level under three quarters of Brooklyn, and locally as much as 50 feet below sea level. In the past decade there has been a gradual diminution in pumping, and increasing artificial recharge through wells,

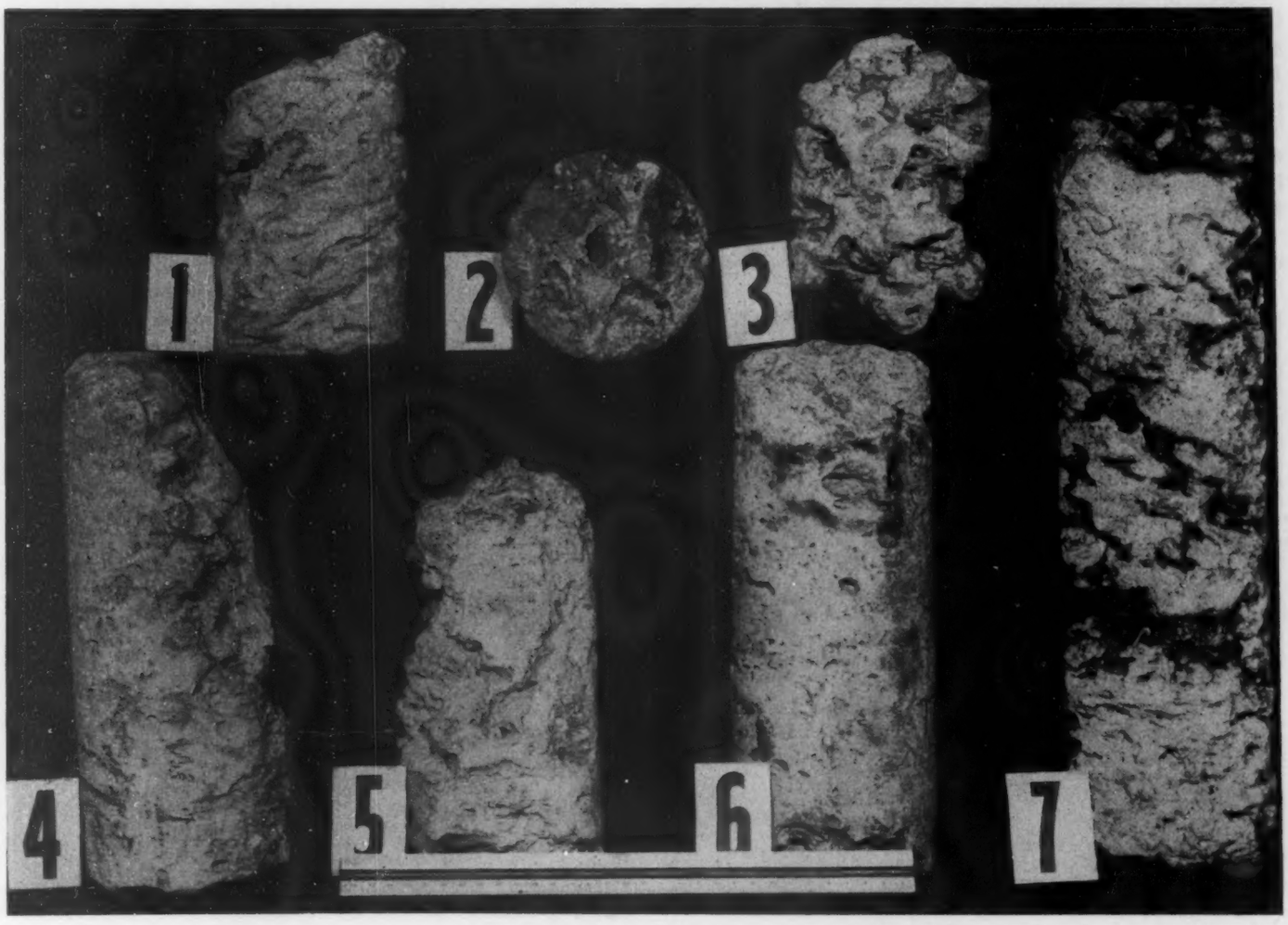

FIGURE 43.—*Cores from test wells in the Miami area, Florida, showing high porosity of the limestone aquifer.*

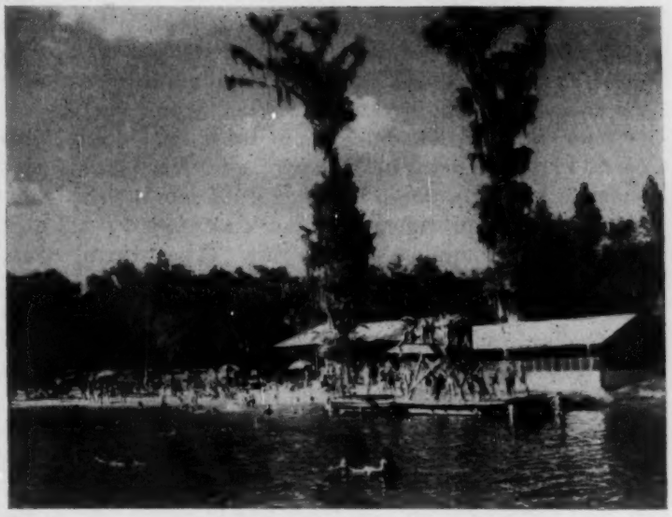

FIGURE 44.—*Kissingen Spring near Bartow, Fla., flowing about 20 million gallons a day in 1947.*

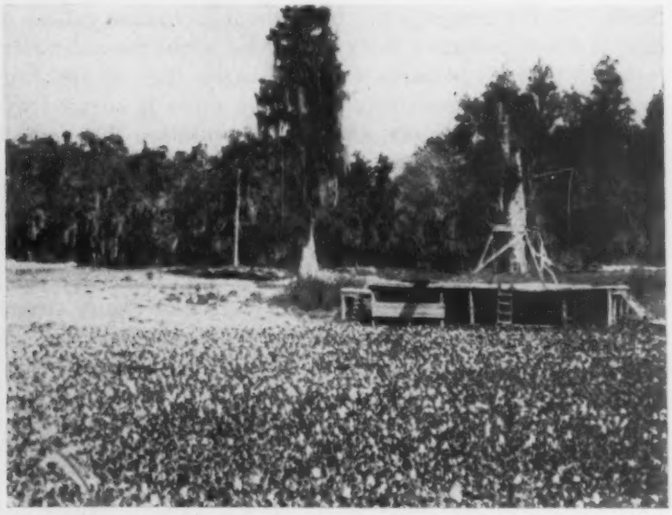

FIGURE 45.—*Kissingen Spring after flow had ceased in February 1950 because of pumping of about 100 million gallons a day from wells.*

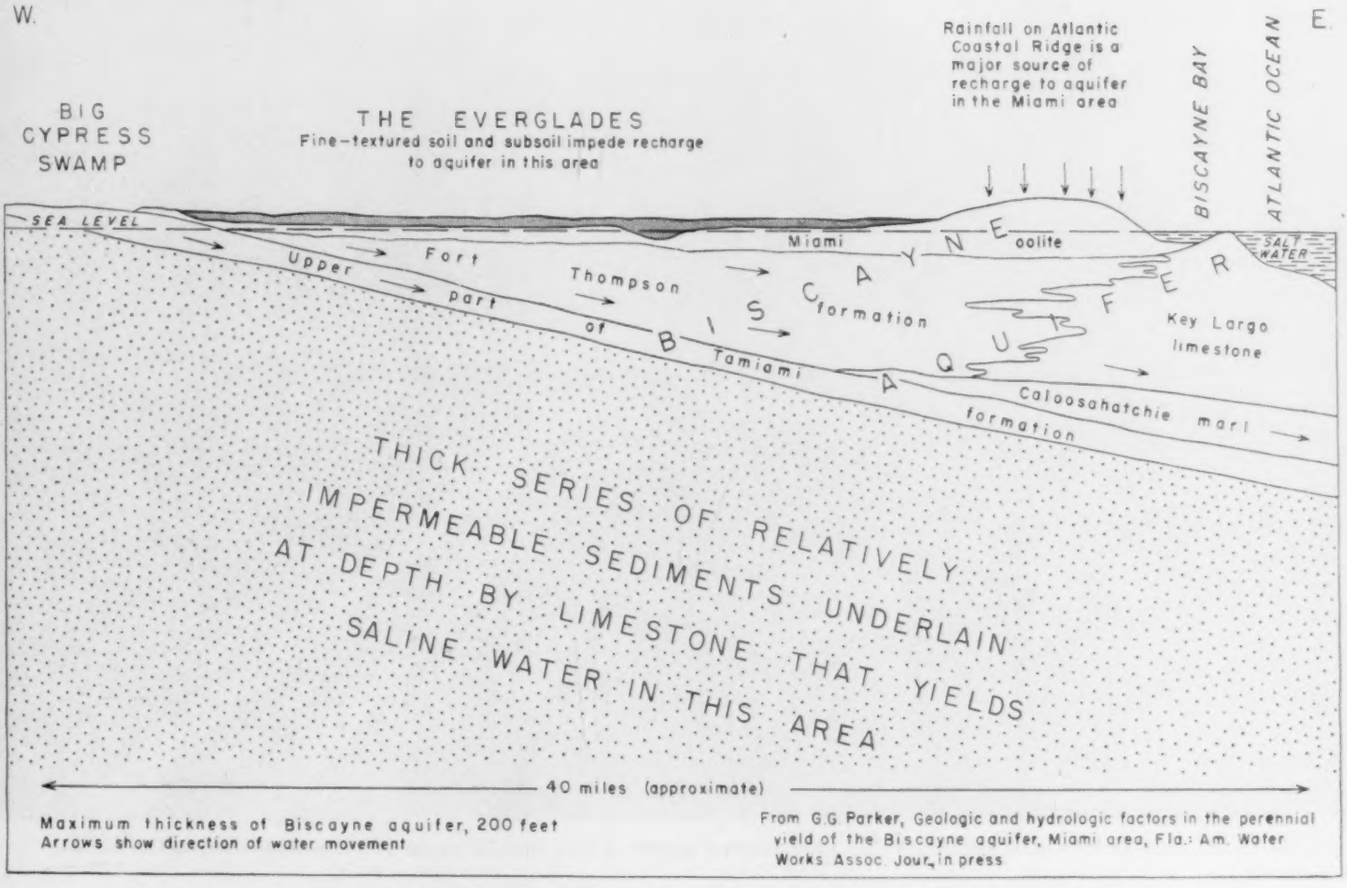
W.
E.
BIG CYPRESS SWAMP
THE EVERGLADES
Fine-textured soil and subsoil impede recharge to aquifer in this area
Rainfall on Atlantic Coastal Ridge is a major source of recharge to aquifer in the Miami area
BISCAYNE BAY
ATLANTIC OCEAN
SEA LEVEL
Upper part of Tamiami formation
Fort Thompson formation
Miami oolite
BISCAYNE AQUIFER
SALT WATER
Key Largo limestone
Caloosahatchie marl
THICK SERIES OF RELATIVELY IMPERMEABLE SEDIMENTS UNDERLAIN AT DEPTH BY LIMESTONE THAT YIELDS SALINE WATER IN THIS AREA
40 miles (approximate)
Maximum thickness of Biscayne aquifer, 200 feet
Arrows show direction of water movement
From G.G. Parker, Geologic and hydrologic factors in the perennial yield of the Biscayne aquifer, Miami area, Fla.: Am. Water Works Assoc. Jour., in press

FIGURE 46.—*Section along the Tamiami Trail, showing water-bearing formations in the vicinity of Miami, Fla.*

and the water table has been rising (Brashears, 1946). Since 1947 the pumpage has been about 30 million gallons a day, of which perhaps a third is returned to the ground-water reservoir through recharge wells and basins (figs. 47 and 48).

About half of Brooklyn's 70 square miles is covered by buildings and pavements, and the precipitation that might replenish the ground-water reservoir under natural conditions goes instead to storm sewers and quickly out to sea. It is estimated that about 35 million gallons a day of potential recharge is thus unable to reach the ground-water reservoir under Brooklyn. Even with this handicap to recharge, the aquifers under Brooklyn evidently receive more than enough replenishment to sustain the present pumpage of 30 million gallons a day, for the water levels in wells have been rising since 1941.

Watercourses

Ground-water reservoirs along stream valleys should be more eagerly—though not necessarily more successfully—sought in the Coastal Plain than in some other parts of the country, because most of the streams of the East are used for disposal of municipal and industrial wastes, and many are highly polluted even before they reach the Coastal Plain. Water from wells along these watercourses may yield water free of bacterial pollution and less contaminated chemically than the water in the stream.

We do not yet know much about the watercourses of the Coastal Plain, but many of them may not be very satisfactory sources of ground water. The sediments deposited by sluggish streams are prevailingly of fine texture and permeable sand and gravel aquifers may be rare. Also, several rivers are tidal and brackish for many miles above their mouths. Wells that are replenished by river infiltration along these tidal reaches would yield brackish water. Saline water has appeared in wells close to the Cape Fear River at Wilmington, N. C., and close to the Mobile River at Mobile, Ala.

Wells along the courses of streams that are heavily contaminated by chemical and industrial wastes are also likely to yield water of inferior quality. For example, the hardness, iron, and sulfate content are increasing in water from some wells in the Philadelphia-Camden area, probably because of coal culm, sludge, garbage, and contaminated waters in the Delaware River channel.

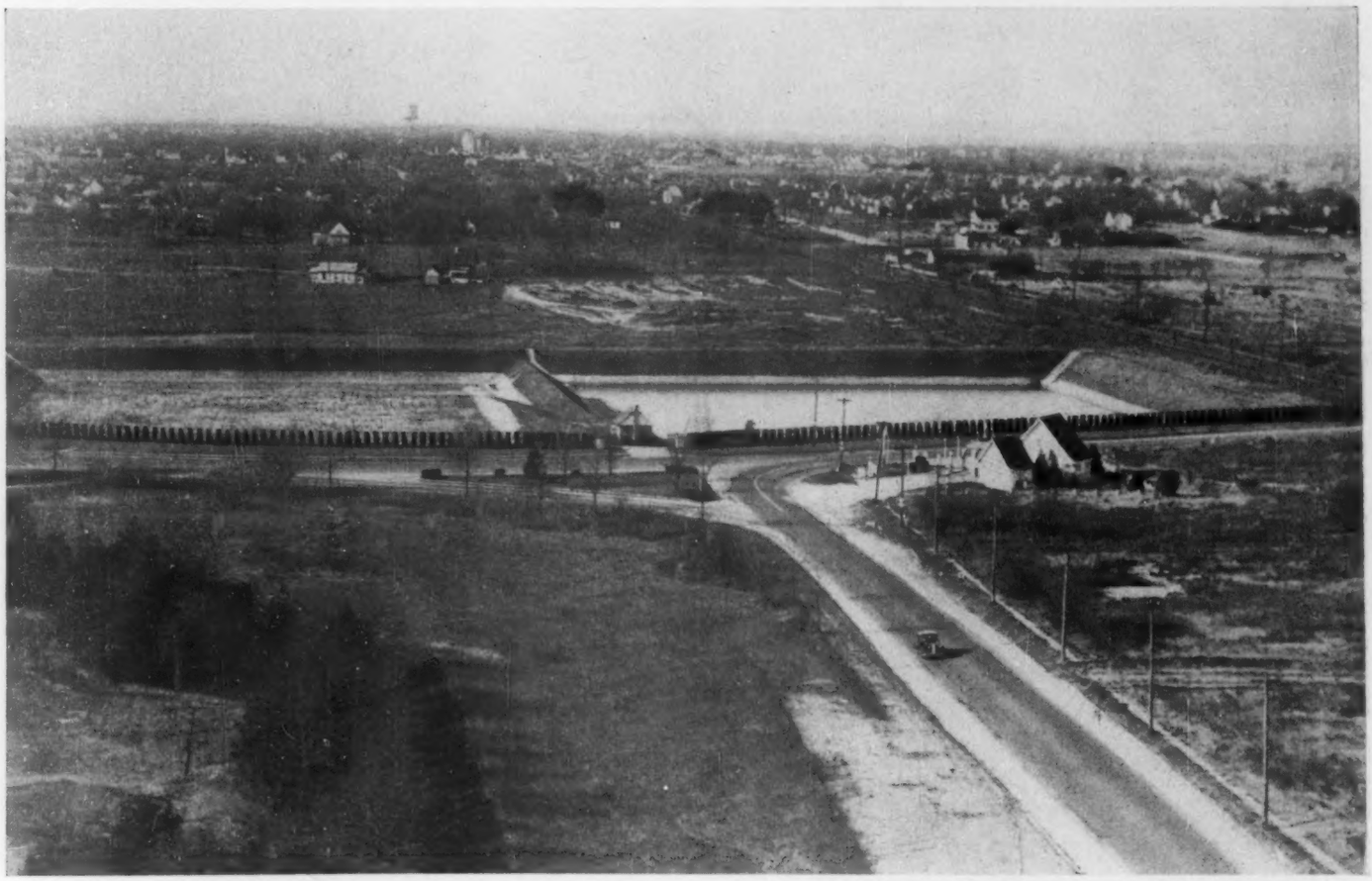

FIGURE 47.—*Recharge basin at Garden City, N. Y. Storm flow in some parts of Long Island is discharged into recharge basins such as this one.*

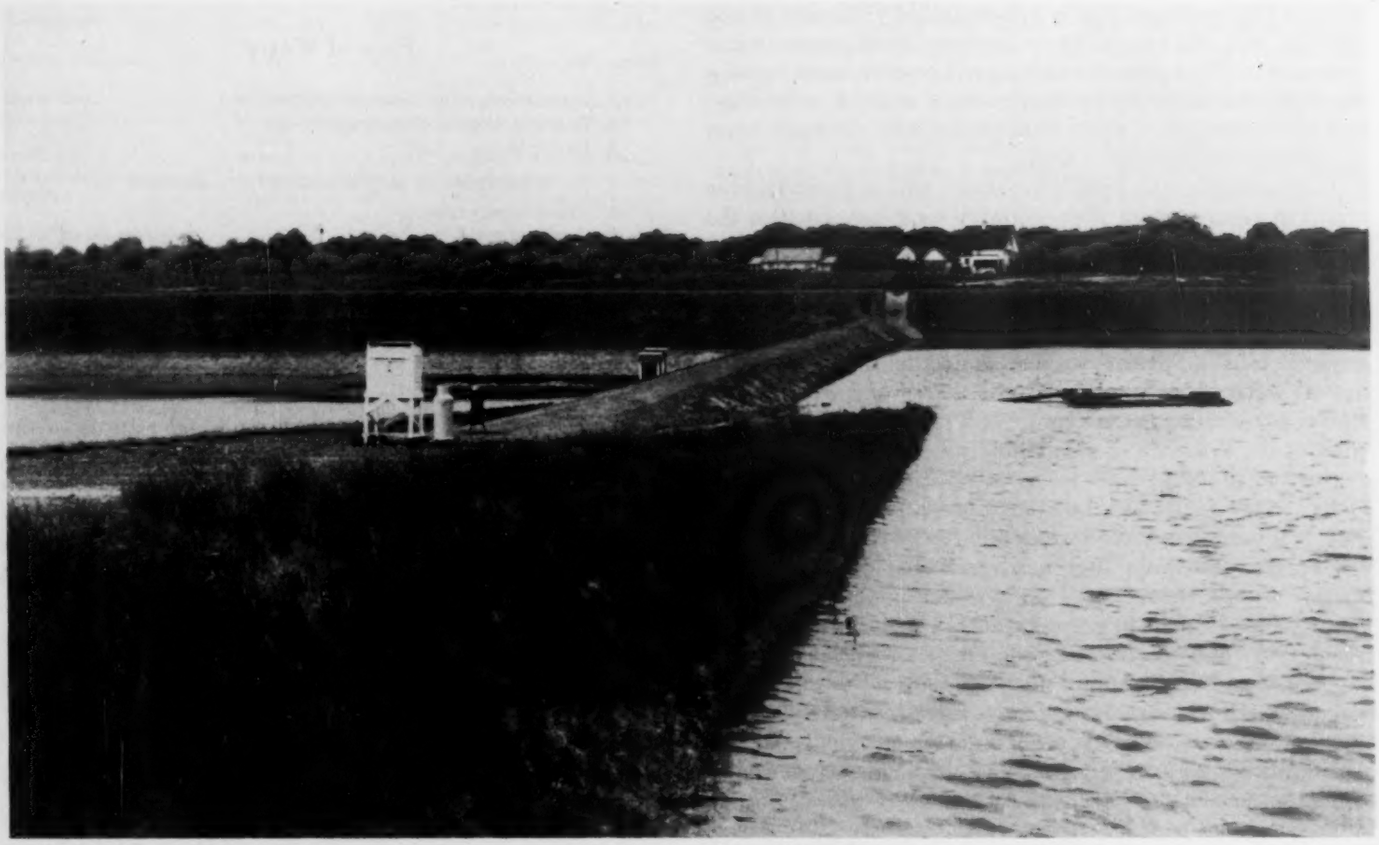

FIGURE 48.—*Recharge basin at Garden City, N. Y. Instrumentation for the purpose of determining quantity of recharge to the ground-water reservoir.*

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Effective Use of Underground Storage Facilities

GROUND WATER serves the needs of a few men with little effort on their part. Some comes to the surface in springs, where it needs only to be diverted to the place of use. Some is near enough to the surface that it can be reached by some crops, as in many subirrigated lands of the West. Many streams that are capable of a well-sustained yield, day in and day out, owe this capability to discharge from ground-water reservoirs. Most ground-water users, however, must develop the water for their use by constructing wells or infiltration galleries or tunnels. These structures divert the water from its natural underground course.

After scanning the conditions under which ground water occurs in various parts of the country, as summarized in the preceding chapter, one may well conclude that the Nation offers a wide variety as to type of aquifer, depth of occurrence, and quantity and quality of ground water that may be obtained. There is also a great variety in the uses that man has made of the Nation's aquifers, for he takes great quantities of water from some and puts water and even liquid wastes into others; ignores some; and probably does not yet know of the existence of a good many.

Most men would like to have security in their water sources; they would like, in other words, to be assured that their wells or springs or streams or reservoirs or what not will provide the water they need year after year. Even a lifetime is not enough, for they would like to pass that security on to succeeding generations. Most water sources can provide this security to some degree, because they are renewed or replenished naturally. Man, in his development and use of the water resources, may elect to limit that use to the quantity that nature is capable of replenishing. Or, as an alternative, he may improve or expand the natural facilities for replenishment. Effective use of an aquifer for sustained yield can be achieved by either method. But either method requires an adequate knowledge of the limitations imposed by nature. The quantity of water yielded by "mining"—withdrawing it at rates greater than it is replenished—cannot be sustained perennially.

Before attempting to shape the Nation's water resources to the needs of man, it is desirable to focus attention upon that vague word "use," which is the justification for all water development. A man may make some use of water in sprinkling a lawn, rowing a boat, flushing a toilet, photographing Niagara Falls, chasing whisky, separating gold from gravel, making nylon, running a steam engine or turbogenerator, fishing, heating his house, or cooling his office. Unless he considers what happens to the water during and after use, it is not possible to state the effect of that use upon the water resources.

The following tables offer certain salient features concerning man's use of water, the limitations of the natural underground facilities, and the potentialities of manipulation of storage in ground-water reservoirs, according to the following outline:

Uses of Water

1. Consumptive and nonconsumptive uses.
2. Disposal after nonconsumptive use.
3. Multiple use.

Limitations of natural underground facilities.

4. Unconfined water.
5. Confined water.

Manipulation of storage.

6. Augmenting natural recharge.
7. Artificial recharge in area of use.
8. Creating space for storage.

1. *Uses of water—Consumptive and nonconsumptive.*[1]—Water used consumptively is "used up" and returns to the atmosphere as water vapor. Consumptive uses include evaporation naturally or in such industrial processes as steam generation, transpiration by vegetation, and perspiration by animals. Water used nonconsumptively remains in liquid state. However, nonconsumptive use takes advantage of certain properties of the water, so that after the use the water may be less suitable for other users desiring to take advantage of the same property.

In the following table many common uses of water are arranged roughly in order of magnitude of the ratio of consumptive to nonconsumptive use.

Common uses of water	Consumptive	Nonconsumptive
Steam generation (locomotive or stationary).	Steam released to atmosphere.	(1).
Air conditioning:		
Evaporative	Cooling achieved by evaporation.	(1).
Recirculating	Some water evaporated with each use.	(1).
Other cooling (recirculating)	do	(1).

[1] With efficient operation, nonconsumptive use is limited to that required for cooling and/or cleaning equipment.

[1] Here we are concerned only with the water that flows by gravity and, therefore, the water that can be obtained from stream or lake, well or spring. Of the water that falls as rain or snow upon the continental area of the United States, more than 70 percent returns to the atmosphere, and doubtless most of this is returned from the soil, without ever having become part of the Nation's surface-water or ground-water (that is, gravity-water) resources. The water held in soil by molecular attraction is of extreme importance to man, for it brings to maturity most of his cultivated crops, and also sustains the native cover of forest, grasses, and brush upon which he depends for a variety of products. Measured in volume of water, the soil moisture used by vegetation of economic value doubtless ranks ahead of all other uses of water for man's benefit.

Common uses of water	Consumptive	Nonconsumptive
Storage in surface reservoirs	Evaporation from water surface.	Seepage underground.
Irrigation by sprinkling	Evaporation and transpiration.	Little seepage.
Irrigation by flooding	Evaporation from ponds, transpiration.	Seepage varies.
Cooking	Steam to atmosphere	Contributes to sewage.
Processing foods, beverages, plastics.	Some water goes into manufactured products.	Carries organic compounds.
Processing:		
Petroleum products	Proportion of consumptive use is increased by reuse of the nonconsumptive water.	Carries chemicals.
Paper and pulp	do	Carries pulp and chemicals.
Chemicals	do	Carries toxic or other chemicals.
Metal products	do	Carries sludge and soluble chemicals.
Atomic fission	Evaporation from tanks	Carries radioactive materials.
Stock watering	Evaporation from tanks and ponds.	Organic wastes into ground.
Drinking	Perspiration	Organic wastes into sewage.
Irrigation by furrow	Evapotranspiration	Dissolves chemicals from soil.
Washing	Evaporation in drying	Carries sediment and soluble matter.
Mining (metals, coal, oil)		Carries natural brines and acids, sediments.
Cooling (once-through)	[2]	Water temperature increased by use.
Air conditioning (once-through).	[2]	Do.
Fish culture	[3]	
Steam heating	[4]	Steam condenses and is reused.
Year-round heat exchange	[4]	Requires storage of water and heat from one season to another.
Sanitation (bath, toilet, dishwasher).	[4]	Sewage carries chiefly organic wastes.
Hydroelectric power	[5]	Takes water toward oceans.
Navigation	[5]	Inland waterways require maintenance of flow.

[2] Increase in water temperature may cause increased evaporation.
[3] Consumptive use by evaporation from water surfaces; may be increased by aerators.
[4] Consumptive use is limited to losses through leaking pipes, valves, etc.
[5] Consumptive use is limited to evaporation from lakes, reservoirs, etc., that are required for continuous operation.

2. *Uses of water—Disposal after nonconsumptive use.*—The effect of consumptive use is to remove the water from the reach of any other potential user. The effect of nonconsumptive use is not so clear-cut, for the water remains with us even though some of its properties are deteriorated by the use. In some instances the deterioration is temporary and may last only a few hours or days. Or it may be minor, so that the waste water is readily diluted by other water, and the entire volume is suitable for further use. On the other hand, some waste waters are contaminated with material sufficiently noxious that when mixed with other water they would render large volumes unsuitable for other uses. The control of water pollution is almost exclusively concerned with the waters that are used nonconsumptively.

The preceding table indicates the principal effects of nonconsumptive use for many purposes. The problems of disposal of nonconsumptively used water are almost innumerable. The following table offers only a few samples.

Some difficulties resulting from disposal of used water

Location, operation, and effect

NEW YORK: *Return of water to aquifer after use for cooling in Brooklyn and Queens.*—Increased temperature of ground water.

OHIO: *Return of water to Mahoning River after multiple use for cooling.*—River temperature increased so that decay of sewage carried by river is inhibited.

PENNSYLVANIA: *Dumping of mining, industrial, and municipal wastes into Schuylkill and Delaware Rivers.*—Highly polluted streams, and increase of soluble materials in water from wells near the river.

PENNSYLVANIA: *Pumping water from mine shafts.*—Acid waters in streams kill fish and make stream unusable for many purposes.

OKLAHOMA: *Dumping oil-well brines into Canadian and Arkansas Rivers.*—Contamination of water in streams and in adjacent wells.

MONTANA: *Irrigation of valley slopes.*—Waterlogging of lower lands.

ARIZONA: *Irrigation in Salt River Valley, mainly east of Phoenix.*—Increased salinity of ground water west of Phoenix.

CALIFORNIA: *Dumping petroleum wastes into abandoned gravel pits near Santa Ana.*—After several years, appearance of hydrocarbons in ground water, forcing abandonment of some domestic wells.

MICHIGAN: *Disposal of pulp by paper mills at Kalamazoo.*—Accumulation on river bottom may impede infiltration to wells upon which industries depend for water.

CALIFORNIA: *Hydraulic mining along Sierra Nevada streams.*—Sediment accumulated in channel downstream, resulting in more and bigger floods.

ILLINOIS: *Air conditioning in Loop district of Chicago.*—Once-through use of water increases peak draft by 50 percent, for not over 1,000 hours per year. Huge water supply and sewage facilities are inevitable.

FLORIDA: *Discharge of phenol wastes into Caloosahatchie River.*—Abandonment of some of Fort Myers' municipal wells.

3. *Uses of water—Multiple use.*—Although water used nonconsumptively creates diverse problems in pollution, it also has possibilities for reuse, and may be used many times. In some instances the use is not affected adversely by the previous use, but in many cases some form of treatment is required before the water can be reused. In general the greatest achievements in multiple use have been made by industries requiring large volumes of water. Here are a few random examples.

Location, achievement, and result

SPARROWS POINT, MD.: *Steel plant uses treated sewage effluent from city of Baltimore.*—Draft from wells reduced by about 10 million gallons daily.

MAHONING RIVER, PA. AND OHIO: *Total water pumped from river by industries may be 10 times the flow in the river, because of multiple use.*—River water reaches high temperature, even in winter.

BISHOP, TEX.: *Recirculation of water in textile plant.*—Plant requires 230 million gallons daily, but 226 million gallons daily is reused.

GENEVA, UTAH: *Recirculation of water in steel mill.*—Plant requires 240 million gallons daily but 233 million gallons daily is reused.

SALT LAKE CITY, UTAH: *Irrigation from ditches at several levels above Jordan River.*—River and low ditches receive return flow from irrigation, which is used again by industry and irrigators.

PORTLAND, OREG.: *Year-round air conditioning with water from wells of different depths.*—Water pumped from cool aquifer in summer is returned to a warmer aquifer after being heated. Cycle reversed in winter. Negligible consumptive use in any season.

NEW YORK CITY, N. Y.: *Conservation devices required on air conditioning systems.*—Reduction in municipal use of water.

DENVER, COLO.: *Effluent from sewage treatment plant discharged into South Platte River.*—Water reused for irrigation downstream from Denver.

4. *Limitations of natural underground facilities—Unconfined water.*—A wide variety of natural and man-made conditions impose limitations upon the uses to which underground reservoirs may be put by man. For some reservoirs, of which those serving Spokane and Dayton may be cited as examples, those limits are so high that water supply is far down on the list of civic worries. But most places are not so fortunate. The following examples indicate how great is this variety in reservoirs where water is *not* confined. These reservoirs are generally capable of replenishment by movement of water downward from the land surface; the limitations in many instances are related to availability of recharge, although other factors may be important also.

Location and limitations of reservoir

IVANPAH VALLEY, NEV.: Recharge negligible, because of desert climate. Practically no natural discharge, and no likelihood of appreciable sustained yield by wells.

GLEN CANYON, UTAH: Recharge not great, because of semiarid climate. No ground-water development, but natural discharge by seeps along deep canyons.

NEWARK, N. J.: Recharge not great because of low permeability of surface materials and constructed surfaces, although climate is humid. Pumping has seriously depleted the reservoir.

CEDAR CITY, UTAH: Recharge in normal years adequate to replenish quantity pumped for irrigation. Inadequate in dry cycles, when pumping causes depletion of the reservoir.

PITTSBURGH, PA.: Recharge by river infiltration abundant when river is at high stage. However, reservoir is too small to hold water for more than the present demand when river is low.

ENID, OKLA.: Moderate recharge to small gravel terrace deposit has furnished adequate water supply for town. Supply now is no less, but town has grown too large for it.

RAHWAY VALLEY, N. J.: Abundant recharge in humid climate. However, development of both ground and surface water in the small drainage basin is great enough to approach the perennial yield.

BROOKLYN, N. Y.: Abundant recharge under natural conditions, but man has impermeated much of the land surface with buildings and pavements, and water from precipitation is sewered to ocean.

HIGH PLAINS, TEX.: Recharge inhibited by impermeable surficial materials. Very heavy pumping, practically all from storage accumulated long ago.

SAND HILLS, NEBR.: Abundant recharge through very permeable sand. However, land not suitable for most agricultural uses because of this great permeability.

SAN LUIS VALLEY, COLO.: Water table in permeable materials can ordinarily be held at any desired depth by control of irrigation water in ditches, with check dams. However, water moves through these permeable materials to waterlog lower lands. Pumping and ditch irrigation were necessary in 1951 because of drought.

MOBILE, ALA.: Adequate recharge by river infiltration, but river is tidal and brackish, and quality of water yielded by some wells is deteriorating.

PONCA CITY, OKLA.: Adequate recharge by river infiltration, but brines dumped in river have forced abandonment of municipal wells.

WILLCOX BASIN, ARIZ.; ESCALANTE VALLEY, UTAH: Desert basin receives recharge from extensive area. Pumping for irrigation is taking some water from storage, yet there is still considerable natural discharge.

FARMS IN MANY AREAS: Relatively impermeable surface materials allow little infiltration, and movement of water through them is slow. Wells may yield enough for drinking, but not enough for modern domestic use.

5. *Limitations of natural underground facilities—Confined water.*—Confined water has generally moved laterally from some other area, and generally therefore the limitations upon development are imposed by the rate of movement of the water from the recharge area. Inadequacy of recharge may also be a factor in some instances. Some reservoirs of confined water are capable of very large sustained yield: San Antonio, for instance, has the advantage of a very productive limestone reservoir, although there has been a considerable reduction in spring discharge during years of drought. There are also many varieties of problem areas, of which the following list is only a small selection.

Location and limitations of reservior

CHICAGO, ILL., GREEN BAY, WIS., and EL DORADO, ARK.: Heavy pumping from closely spaced wells has lowered artesian pressures by hundreds of feet. This lowering is still going on.

ROCKFORD, ILL., and MINNEAPOLIS, MINN.: Heavy pumping in a small area caused a progressive lowering of artesian pressure for several decades, but there has been no decline in recent years. Aquifer is still discharging water to streams draining the area.

HOUSTON, TEX.: Very heavy pumping has lowered artesian pressures markedly, but has also increased the lateral movement of ground water into the area.

LONG BEACH, CALIF.: Heavy pumping has lowered artesian pressures markedly, but there has been no increase in inflow of fresh water, because of pumping nearer to recharge area. However, ocean water has moved in.

TAMPA, FLA.: Aquifer is a very permeable limestone, and concentrated draft near coast induced inflow of saline water, causing abandonment of municipal wells.

ACADIA PARISH, LA.: Aquifer is covered by clay impermeable enough to be suitable for rice growing, and recharge area is many miles away. Lowest part of aquifer has saline water, and in areas of heaviest pumping water from wells is increasing in salinity.

MIAMI, OKLA.: Water is confined beneath impermeable layers, and lateral movement is impeded by natural barriers. Decline of artesian pressure due to pumping has accelerated in recent years.

WINTER GARDEN, TEX.: Artesian pressures have declined because of withdrawals from wells; water table in recharge area has also been lowered in recent dry years, indicating inadequacy of natural replenishment.

MILL CREEK VALLEY, OHIO: Artesian pressures have declined because of pumping; water table in recharge area has also been lowered considerably, by pumping there.

EASTERN NORTH DAKOTA: High initial artesian pressures have been dissipated because of flow from deep wells distributed over a wide area. These wells tap a poorly permeable sandstone.

BALTIMORE, MD.: Reduction of artesian pressure in deep aquifer has permitted entry of inferior water from a shallower aquifer, through leaky wells.

6. *Manipulation of storage—Augmenting natural recharge.*—By far the greatest part of the effort in developing ground-water reservoirs has been devoted to getting water out of them. Nevertheless, many aquifers have received more recharge than would have entered them by natural processes, because of man's activities. This artificial recharge in some instances is the main purpose of the activity; in others it is a byproduct of his development and use of water for various purposes.

Artificial recharge of many aquifers has been accomplished by augmenting the natural recharge: water has been applied

upon the recharge area in quantities greater than would be available by natural processes. From the following list it appears that California leads in projects for intentional recharge, but the unforeseen effects of artificial recharge are rather widespread.

Location and methods of augmenting natural recharge

SAN BERNARDINO, CALIF.: Surplus surface waters are spread over gravels of upper Santa Ana River Valley. Since 1912 the quantity has averaged 15,000 acre-feet a year, and was 68,000 in 1922.

LOS ANGELES COUNTY, CALIF.: Flood-control reservoirs fill only in time of flood, and then release water at rates suitable for maximum infiltration and ground-water recharge.

SAN FERNANDO VALLEY, CALIF.: In this ground-water reservoir, the city of Los Angeles has stored floodwaters from several flood-control projects, as well as surplus water from the Owens Valley aqueduct. In 1944, water levels in representative wells were 25 to 50 feet higher than in 1931, owing to increases in storage during the wet years 1936 to 1943.

TWIN FALLS, IDAHO: Ground-water storage has been increased by more than 6,000,000 acre-feet since 1905, by seepage from land irrigated with Snake River water. Water table has risen more than 200 feet in some areas, and is close enough to the surface that drains have been installed. Water from these drains is also appropriated for use.

MINIDOKA, IDAHO: About 600,000 acre-feet of Snake River water is applied annually for irrigation, of which a sizable proportion seeps to the ground-water reservoir. This is shown by the discharge from the reservoir at Thousand Springs, where discharge has increased more than 30 percent since 1902.

CACHE VALLEY, UTAH: Surface water is used to irrigate crops upon the recharge areas of artesian aquifers. Artesian pressures in wells reach their seasonal peak in August. It is likely that storage in the ground-water reservoir has increased since the valley was settled, even though wells now draw about 20,000 acre-feet from it annually.

HELENA VALLEY, MONT.: Much surface water is diverted and used on the valley slopes for irrigation. Once-fertile bottom lands have become waterlogged in the process, because of movement of ground water from the higher irrigated lands.

MCMILLAN RESERVOIR, N. MEX.: McMillan Reservoir contributes materially to an underlying ground-water reservoir in limestone. The Major Johnson springs discharge five to eight times as much water from this limestone when McMillan Reservoir is full as when it is empty.

POWELL, WYO.: Town obtains its municipal water supply from gravel which is recharged chiefly by deep penetration of water used for irrigation in the Heart Mountain project of the Bureau of Reclamation. Prior to the development of this project the water in the gravels was of an inferior quality, unsuitable for domestic use.

7. *Manipulation of storage—artificial recharge in area of use.*—Wherever the ceiling on ground-water development is set by the rate at which water can move through an aquifer, any improvement in the natural facilities for replenishment will probably involve bypassing those transmission difficulties. Augmenting the natural recharge may be meaningless, and will be impossible in those places where the aquifer is already rejecting some of the water available for recharge.

In such situations it may be possible to put water into the aquifer in the area where it is later to be withdrawn for use. Here are some examples:

Location and achievement

LOUISVILLE, KY., and NEWARK, N. J.: In an area where ground water is used for cooling, and where low-water temperature is therefore desirable, cold municipal water is recharged throughout the winter, into wells that will be pumped chiefly in summer.

LONG ISLAND, N. Y.: In an area where ground water is used chiefly for air conditioning, it is returned through recharge wells to the same aquifer from which it was pumped. Returned water raises the temperature of water in the aquifer, but the temperature appears to be nearing a new equilibrium and will not rise indefinitely.

DES MOINES, IOWA: Municipal water supplies come from an infiltration gallery dependent largely upon river infiltration, and the supply diminishes when the river is at low stage. For more than 40 years those supplies have been supplemented by recharge from flooding basins near the gallery, filled with water from the river.

LINDSAY, CALIF.: An irrigation district has been pumping at rates greater than replenishment, which is derived largely from a river more than 10 miles away. Ground water was artificially replenished during one winter by pumping from wells near the river and recharging through the district's irrigation wells.

MIDDLESEX COUNTY, N. J.: Recharge ponds constructed by the Perth Amboy Water Works and by the "Duhernal" companies (Dupont, Hercules Powder, National Lead) add as much as 15 million gallons per day to an intensively developed ground-water reservoir.

PLATTE RIVER VALLEY, NEBR.: The natural supplies of many wells have been augmented by downward percolation of irrigation water diverted from a river.

SEABROOK, N. J.: Wash water from a frozen-food packing plant is sprayed with much of its contained vegetable matter over forested dune lands. Rate of application is about 8 inches per day and has reached 1,200 inches per year in some areas. This very heavy artificial rain encourages pine, locust, and lambsquarter at the expense of huckleberry and some oak. Water reaching the ground-water reservoir is reported to be of good quality, and devoid of organic contaminants.

WASCO, CALIF.: In experimental water-spreading operations by the Soil Conservation Service, the sandy loams of southern San Joaquin Valley absorb water at rates that reach a maximum of about 40 inches per day after 10 days, then decrease to less than 6 inches after 4 months. In the third season after an application of cotton-gin trash, the infiltration rate reached a maximum of 90 inches per day at the end of a month, and declined to 50 inches per day at the end of 4 months.

AZUSA, CALIF.: Effluent from the sewage-treatment plant, about 450,000 gallons per day is discharged into recharge basins in coarse gravels of San Gabriel River alluvial fan. Biochemical oxygen demand of the effluent ranges from 10 to 30 parts per million but tests show negligible B. O. D. at depths of 5 feet or more below the ponded water. Depth to water table is more than 200 feet.

8. *Manipulation of storage—creating storage space.*—The creation of storage space involves the depletion of ground-water reservoirs in places where they can subsequently be recharged readily by natural processes. The operation sounds contrary to that of artificial recharge, which is devoted to *increasing* the quantity of ground water in storage. Nevertheless in the right places it may serve the same ultimate purpose of increasing the total water supplies available for man's use perennially.

For surface water the creation of storage space is basic in flood-control projects, for with it man can overcome the

excesses of nature by accumulating floodwaters and then releasing them slowly enough that they can cause no damage, and may well be of some benefit. Creation of storage space in the soil is analogous, and it too may be important in flood control. As an example, a vegetative cover may increase the infiltration and permeability in the surficial zone and deplete the soil moisture therein, so that the ground can readily absorb water from precipitation. Where this occurs, the vegetative cover may be an effective means of flood control.

Creation of storage space in ground-water reservoirs may also be effective in flood control, and at the same time increase the quantity of water available on a sustained-yield basis. The ground-water reservoirs most susceptible to manipulation for flood control are those along watercourses.

Location and operation

ARKANSAS RIVER VALLEY, KANS.: Pumping for irrigation has depleted the ground-water reservoir of the valley so greatly that floods passing Syracuse (Kans.) have been largely absorbed before they reached Garden City. Only the largest floods continue as far downstream as Larned, and these have greatly reduced crests.

CANTON OHIO.: City has developed perennial supply of 10 million gallons a day from a buried valley having large storage capacity but little recharge. This deep aquifer is recharged artificially by wells that take water from shallow gravels along a small creek. When the creek is in flood these recharge wells deliver as much as 18 million gallons a day to the developed aquifer.

LIVERMORE VALLEY, CALIF.: This is one of several valleys in California where the ground-water reservoir has been seriously depleted by pumping for irrigation. But during the winter rainy season streams tributary to the valley carry water, unused, to the ocean, and sometimes with flood damage. The depleted ground-water reservoir offers opportunity for storage of these floodwaters for future use.

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